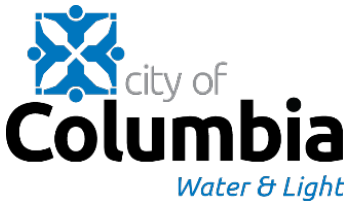




Pilot Testing and Alternatives Analysis Report

City of Columbia, Missouri
McBaine Water Treatment Plant
Improvement Project

October 8, 2021



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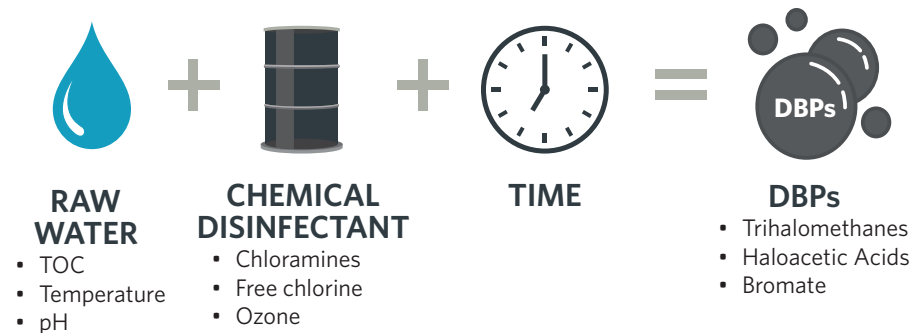
Columbia McBaine Water Treatment Plant Pilot Testing and Alternatives Analysis

The following is a graphical summary of the bench-scale and pilot-scale testing that was completed as part of the City of Columbia's Alternative Analysis.

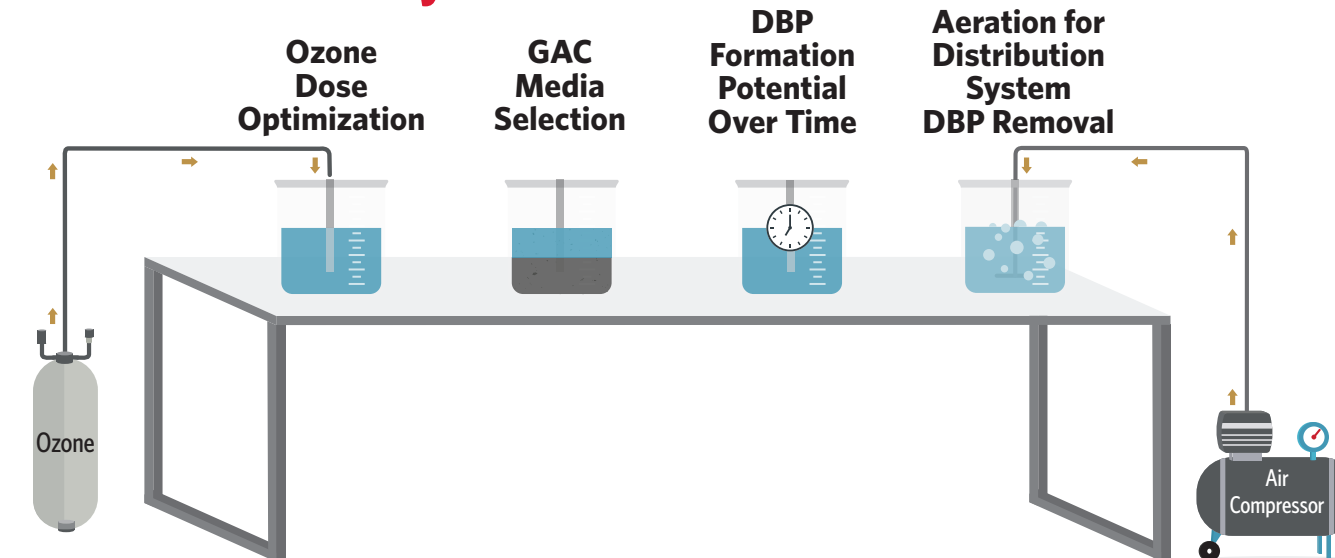
Acronyms

BAF = Biologically Activate Filtration MGD = Million Gallons per Day
DBP = Disinfection Byproduct SDS = Simulated Distribution System
GAC = Granular Activated Carbon TOC = Total Organic Carbon
MCL = Maximum Contaminant Limit WTP = Water Treatment Plant

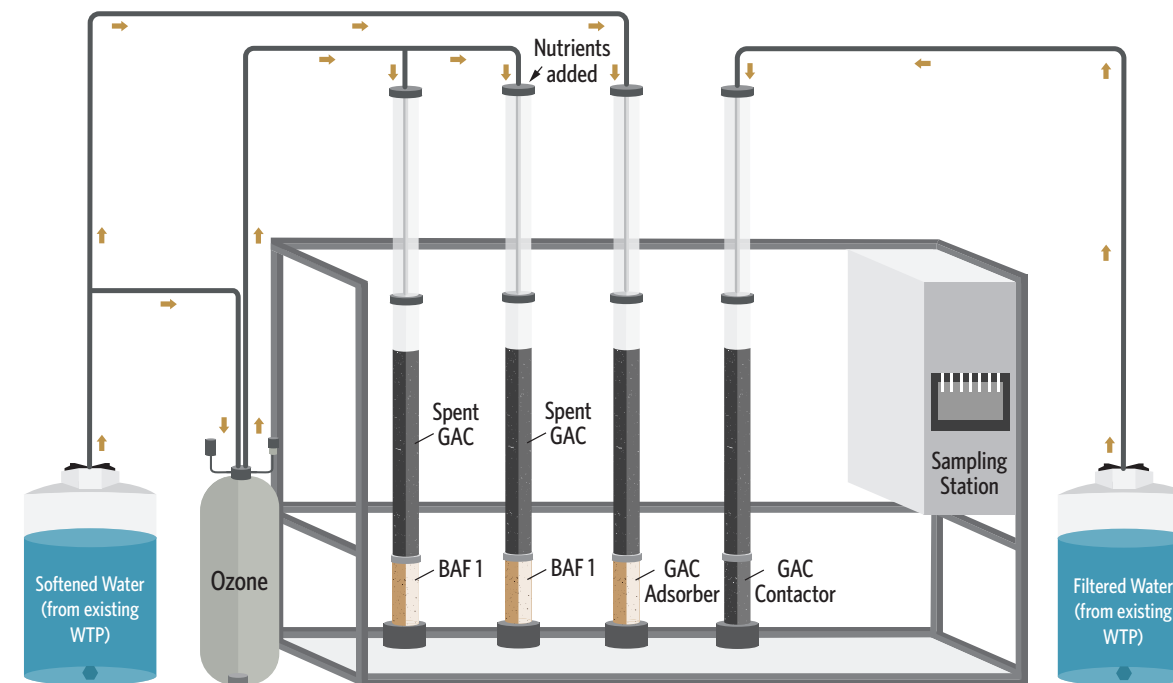
DISINFECTION BYPRODUCT FORMATION



Bench-Scale Study

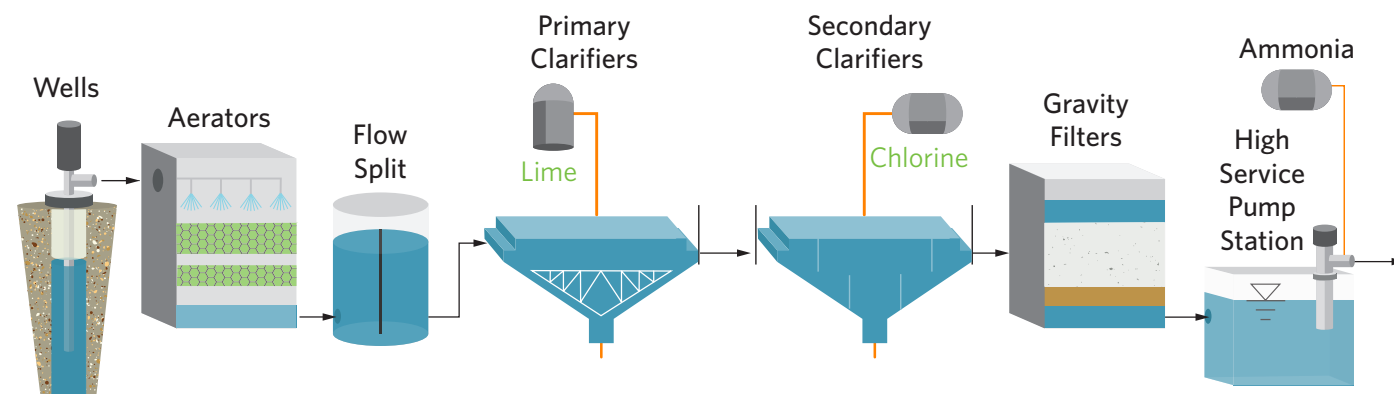


Pilot-Scale Study

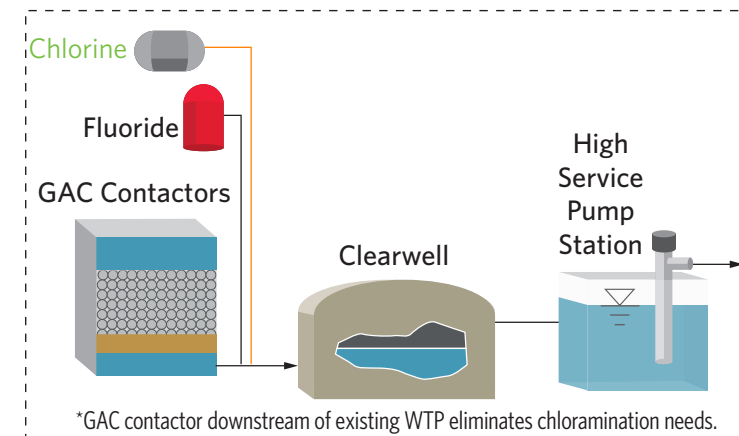


Water Treatment Process Flow

EXISTING WATER TREATMENT PLANT



FUTURE POTENTIAL IMPROVEMENT - GAC CONTACTOR*



Executive Summary

The City of Columbia's McBaine WTP is a 32 MGD groundwater treatment facility with a process train that includes aeration and lime softening, followed by conventional filtration, free chlorine primary disinfection, and chloramine secondary disinfection. The distribution system operates effectively with chloramines as the residual disinfectant.

The City originally employed free chlorine disinfection, then converted to chloramination to minimize DBP formation from the reaction between organic carbon and free chlorine in the distribution system. There has been some interest in the community to revert to free chlorine. In order for the City to revert back to free chlorine for secondary disinfection, the WTP will need to further remove the organic compounds that affect DBP formation potential to remain compliant with current and possible future regulations. The purpose of this pilot was to determine the treatment required and the recommended technology to revert to free chlorine secondary disinfection.

Bench-scale and pilot-scale testing were performed to determine the technologies capable of reducing finished water TOC and, in turn, DBP formation potential (specifically, total trihalomethanes and haloacetic acids). Three pilot trains were evaluated: post-softening ozonation with BAF, post-softening with GAC filter adsorption, and post-conventional filtration GAC adsorption.

Pilot data was used to establish a relationship between routinely monitored water quality criteria, such as TOC, and DBP formation potential. This correlation allows for real time assessment of treatment performance. Ultimately, a TOC goal of 1.2 mg/L was determined to maintain DBP formation potential below the existing National Primary Drinking Water Regulations MCLs. However, additional TOC reduction will be necessary to maintain the City's current DBP levels with chloramination, if this baseline is established as a water quality goal. SDS testing demonstrated that:

- Haloacetic acid formation potential was below the MCL for all pilot trains.
- Trihalomethane formation potential was not significantly reduced for the ozone with BAF. The existing site conditions may have impacted the biological treatment performance due to solids carryover from the current softening process. These solids can create scaling of the BAF media, potentially limiting the biology formation and contaminant treatment.
- Initially, GAC filter adsorbers effectively reduced trihalomethane formation potential below the MCL. However, TOC removal reached steady-state operation after 100 days, resulting in trihalomethanes concentrations above the MCL.
- GAC contactor outperformed all other pilot treatment trains for TOC and DBP removal. Based on current WTP TOC removal, GAC media will likely need replacement once every 7 months. If the upcoming WTP improvements result in enhanced TOC removal, GAC replacement intervals may be extended, thus reducing operational costs.

The findings from this study were used to recommend GAC contactors as a treatment alternative capable of achieving the water quality and treatment performance necessary.

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1 Introduction

1.1 Project Background

The City of Columbia, Missouri (the City) owns and operates the McBaine Water Treatment Plant (WTP), which has served the City for more than 50 years. The plant's rated capacity is 32 million gallons per day (MGD) and the existing treatment process consists of aeration and lime softening followed by conventional filtration, free chlorine primary disinfection, and chloramine secondary disinfection, as shown in Figure 1-1. The WTP requires improvements to address the aging equipment, remove hydraulic limitations, improve operational efficiency, and enhance finished water quality. Refer to the Preliminary Engineering Report for more details regarding the current improvement project. In parallel to the current improvement project, the City is evaluating the viability of removing total organic carbon (TOC) to minimize the formation of disinfection byproducts (DBPs), such as total trihalomethanes (TTHMs) and haloacetic acids (HAA5).

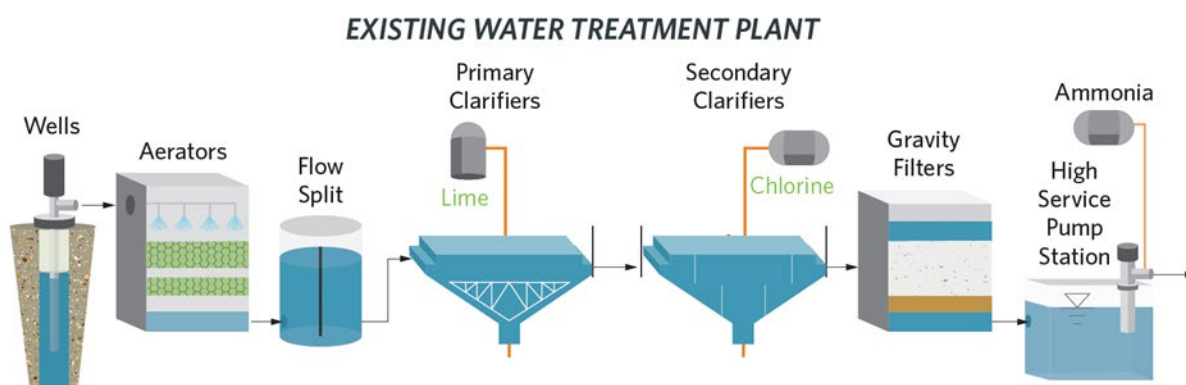


Figure 1-1 McBaine WTP Existing Process Flow Diagram

1.2 Alternative Treatment Analysis (Treatment Technology Analysis)

1.2.1 Purpose

The purpose of the alternative treatment analysis was to evaluate process enhancements to meet long term water quality targets. A pilot study is the foundation for identifying the appropriate treatment technology to address future needs and improvements. Treatment technologies that may potentially achieve the anticipated future water quality targets were evaluated as part of the Alternatives Analysis. This analysis included developing a site plan layout, hydraulic analysis, concept design, and capital, operating, and life cycle cost estimate for the recommended alternative. The Alternative Treatment Analysis occurred in parallel with the current design of WTP improvements to align the current filtration and high service pumping improvements with the proposed future enhanced treatment technology.

A pilot study was performed to determine the technologies capable of enhanced TOC removal and, in turn, DBP formation reduction potential (specifically, TTHMs and HAA5). DBPs are formed when disinfectant chemicals react with organic compounds or DBP precursors that are present in the water.

DBPs include known or suspected carcinogens that may lead to health effects such as cancer, potential reproductive system effects, as well as liver, kidney, and nervous system problems. Select TTHMs and HAA5 have been regulated by the United States Environmental Protection Agency (USEPA), with established drinking water maximum contaminant limits (MCLs) of 80 and 60 µg/L, respectively. Total organic carbon (TOC) and UV₂₅₄ absorbance serve as precursors for these DBP contaminants, which can be used as surrogates for the DBP formation potential. These DBP precursors are shown to be good surrogates for unregulated contaminants of emerging concern (CEC), such as pharmaceuticals and personal care products, pesticides, and industrial solvents. It is likely that EPA will enact a Stage 3 Disinfection By-product Rule in the future. Enhanced TOC removal and DBP reduction will strengthen compliance with future regulations. Previous studies and full-scale industry practice have demonstrated that treatment technologies such as ozone, biologically active filtration (BAF), and granular activated carbon (GAC) can be highly effective in the removal of recalcitrant DBP precursors.

1.2.2 Future Water Quality Considerations

A water quality workshop was conducted as part of the initial alternative treatment analysis evaluation. During this workshop, considerations were developed for future finished water quality characteristics. These water quality considerations are presented in Table 1-1. The considerations include parameters for TOC and DBPs based on the existing treatment processes at the WTP and potential upcoming USEPA DBP regulations. These water quality considerations were used to evaluate the performance of pilot treatment processes and refined based on the pilot results.

Table 1-1: Future Finished Water Quality Considerations

Parameter	Current Regulatory Standard (GW)	Current Finished Water Quality Goals	Future Finished Water Quality Considerations
pH (St. Units)	6.5 to 8.5 SMCL	8.5 to 8.8 ¹	8.5 to 8.8 (can be impacted by secondary disinfectant goal)
Free Chlorine Residual (mg/L)	Meet CT Requirements for Virus and Giardia Inactivation ³	Minimum 2X Inactivation Ratio Under Worst Case Conditions of Temperature and pH	Minimum 2X Inactivation Ratio Under Worst Case Conditions of Temperature and pH
Alkalinity (mg/L as CaCO ₃)	Finished Water Stability	140 ²	140 (tied to hardness goal)
Virus	> 4.0 Log Removal/Inactivation	> 4.0 Log Removal/Inactivation	> 4.0 Log Removal/Inactivation
Giardia ³	N/A ³	> 3.0 Log Removal/Inactivation	> 3.0 Log Removal/Inactivation
Cryptosporidium ³	N/A ³	> 2.0 Log Removal/Inactivation	> 2.0 Log Removal/Inactivation
Total Hardness (mg/L)	N/A	150	TBD
Calcium Hardness (mg/L)	N/A	TBD	TBD
Magnesium Hardness (mg/L)	N/A	TBD	TBD
Iron (mg/L)	SMCL = 0.3 mg/L	< 0.3 mg/L	< 0.3 mg/L
Manganese (mg/L)	SMCL = 0.05 mg/L	< 0.03 mg/L	< 0.03 mg/L
TOC (mg/L) ³	N/A ³	> 15% removal	< 1-1.2 mg/L
Turbidity (NTU)	N/A ³	≤ 0.3 NTU for 95% of reading. Not to exceed 0.5 NTU	≤ 0.1 NTU
Bromate (mg/L)	≤ 10 µg/L RAA	≤ 10 µg/L	< 5 µg/L
Fluoride (mg/L)	< 0.7	< 0.7	< 0.7
CECs ⁴	N/A	N/A	TBD

¹ Depends on Secondary Disinfection Strategy

² Depends on hardness goal

³ McBaine WTP is currently regulated as a groundwater treatment plant

⁴ Contaminants of emerging concern

1.2.3 Pilot Study Objectives

The pilot study's objectives included a desktop analysis, bench-scale testing, and pilot-scale evaluations. The specific objectives for each of the testing regimes are summarized below and discussed in more detail in Sections 3.1 and 4.1.

Desktop Analysis

A desktop analysis was completed to evaluate the viability of enhanced lime softening to achieve future finished water quality considerations. Full-scale testing of enhanced lime softening was considered; however, it was not implemented due to the operational complexities, anticipated chemical consumption, anticipated excess solids production, and potential finished water quality impacts.

Bench-scale Testing

Bench-scale testing is typically completed on a small-scale, such as in a laboratory. The standard purpose for bench-scale testing is to verify that a particular treatment process can be safely performed and yield the desired results prior to implementing larger scale testing. Bench-scale testing was conducted on raw and softened water shipped from the McBaine WTP to the HDR Water Quality Laboratory. The testing objectives included ozone demand and decay testing, GAC isotherm testing, simulated distribution system testing, and air stripping.

Pilot-scale Testing

Pilot-scale testing is completed at the water treatment plant using pilot skids, which are small-scale models of full-size treatment processes. The skids are typically provided by an equipment vendor, pilot system fabricator, or custom-built by a contractor. The bench-scale results informed operating parameters and media selection for the pilot-scale testing. Pilot-scale testing was conducted on post-secondary/filter influent and filter effluent. The pilot-scale testing included one (1) ozone skid and one (1) filter/GAC skid with four (4) columns. The treatment schemes piloted included ozone/biofiltration, GAC filter adsorber, and post-filtration GAC contactor.

This report presents the purpose for and results obtained from bench-scale and pilot-scale testing at the WTP.

2 Desktop Analysis

A desktop analysis was completed to evaluate the viability of enhanced lime softening to achieve future finished water quality considerations. Full-scale testing of enhanced lime softening was considered; however, it was not implemented due to operational complexities, anticipated chemical consumption, anticipated excess solids production, and potential finished water quality impacts. Three (3) of the four (4) existing clarifiers are not capable of operating in enhanced lime softening mode. This mode would involve solids recycling, higher solids concentrations, and the ability to develop and maintain a sludge blanket. Full-scale testing would have required the use of Primary Clarifier No. 4, which has a minimum design flow of approximately 4 MGD. Discharging this volume of flow to waste and at the volume of softened water with a water chemistry differing from the other softening basins concerned the City's Operations staff. Enhanced lime softening requires the clarifiers to operate at elevated pH levels (up to 11 SU). While the existing lime feed system is capable of elevating pH in the basin, the existing facility does not have a carbon dioxide or equivalent chemical feed system capable of reducing the pH to the 8.5 SU range, thereby, quenching the lime softening process and stabilizing the water feeding the filters. Lastly, operating in enhanced softening mode produces more solids, which also concerned Operations staff based on current solids inventories and limitations of land application contractors.

Columbia's raw water TOC ranges from 1.0 to 3.5 mg/L, with an average of approximately 2.5 mg/L. As noted in Section 1.2.2 above, the future finished water quality consideration for TOC is 1.0 to 1.2 mg/L, requiring a reduction of 52 to 60 percent (at a raw TOC of 2.5 mg/L) and 65 to 71 percent (at a raw TOC of 3.5 mg/L). For groundwater supply sources, such as the City of Columbia's groundwater supply, it is generally recognized that full or enhanced lime softening (to pH of approximately 11) can achieve a TOC reduction of approximately 30 to 35-percent¹. Groundwater generally contains more dissolved organic carbon, which can be more difficult to remove. With the addition of alum or other coagulant dosages of 10 to 15 mg/L, up to an additional 15-percent of TOC removal is possible. Therefore, the total TOC removal achievable with enhanced lime softening is expected to be between 45 and 50-percent. While enhanced lime softening may prove to be beneficial for increased TOC removal, it is not expected to positively achieve the project goals under all water quality conditions.

¹ Based on a series of experiments by LIAO and Randtke (1985)

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3 Bench-scale Testing

3.1 Objectives

Bench-scale testing was conducted on raw and softened water shipped from the McBaine WTP to the HDR Water Quality Laboratory. The testing was completed prior to and in parallel with the pilot-scale testing, as summarized in Section 4. Bench-scale testing objectives included:

- Ozone Demand and Decay Testing: Examined the effectiveness of using ozone for DBP control in raw and softened water including a bromate formation analysis.
- GAC Isotherm Testing: Examined the TOC removal effectiveness and DBP formation potential for three (3) different GAC media types in post-filtration water to determine the preferred GAC for pilot-scale testing.
- Simulated Distribution System (SDS) Testing: Examined the relationship between TOC concentration and subsequent DBP formation in GAC-treated sample water over time.
- Air Stripping Testing: Examined the effectiveness of air stripping to remove TTHMs from post-filtration water. SDS studies were conducted to simulate air stripping within the City's distribution system reservoirs to determine TTHM formation potential that can occur downstream of aeration.

3.2 Ozone Demand/Decay Testing

Phase I of the testing examined the ability for ozone treatment to reduce TOC and UV₂₅₄ absorbance and the potential of bromate formation resulting from the ozonation.

3.2.1 Water Quality Characterization and Testing Procedures

Table 3-1 provides a list of the water quality parameters measured in the sample water upon its arrival at HDR's Water Quality Laboratory. It should be noted that the UV₂₅₄ measurements for the bench-scale testing were analyzed by Eurofins Eaton Analytical.

Table 3-1: Pre-Ozone Testing, Source Water Characterization

Water Quality Parameter ¹	Laboratory Method
TOC	SM5310C/E415.3
UV ₂₅₄	SM5910
Bromide	EPA300
Ammonia	EPA350.1
Total Iron	EPA200.7
Dissolved Iron	EPA200.7
Total Manganese	EPA200.8
Dissolved Manganese	EPA200.8

¹ Measurements conducted by Eurofins Eaton Analytical, Monrovia, CA

Ozone Testing was conducted according to the following steps.

1. A stock ozone solution was prepared in a fume hood:
 - a. A custom-built Guardian ozone generator was fed with oxygen gas and used to produce ozone up to approximately 14 percent. Produced ozone was bubbled through a 1 L jacketed reservoir, which was filled with deionized (DI) water, and chilled to approximately 2°C.
 - b. The gas released from the reservoir was captured from the outlet and run through two gas scrubbing bottles filled with potassium iodide (KI) solution (approximately 100 g/L) to quench any escaping ozone.
 - c. The stock solution was bubbled for approximately 30 minutes, and the resulting solution (approximately 80 mg/L as ozone [O₃]) was measured using the HACH Indigo Method (Method 8311).
2. Water samples were brought to room temperature in sealed, amber glass bottles (reactors) prior to ozone testing.
3. Ozone reactors were dosed with ozone at the following concentrations: 0.5, 1.0, 2.0, 3.0, and 4.0 mg/L.
4. Ozone decay curves were generated at the following intervals: 1, 2, 3, 5, 7, and 10 minutes.
5. At 10 minutes, samples were taken for the analytics outlined in Table 3-2.

Table 3-2: Ozone Testing Analytics

Water Quality Parameter	Ozone Reaction Time (min.)	Laboratory Method
Ozone decay	1, 2, 3, 5, 7, and 10	HACH Method 8311
TOC ¹	10	SM5310C/E415.3
UV ₂₅₄ ¹	10	SM5910
Bromate ¹	10	EPA300

¹ Analyses conducted by Eurofins Eaton Analytical

3.2.2 Bench-Scale Ozone Results

Table 3-3 illustrates the initial water quality characteristics of settled water that was collected for ozone testing. Figure 3-1 further illustrates the decay profile at the five ozone dose concentrations (0.5 to 4.0 mg/L). Ozone doses of 0.5 and 1.0 parts per million (ppm) resulted in negligible ozone residual, even after only 30 seconds. An ozone dose as high as 4.0 ppm demonstrated a significant residual (0.5 ppm) by 10 minutes of contact time.

Table 3-3: Pre-Ozone Analytics on Settled Water

Water Quality Parameter ¹	Analytical Result
TOC (mg/L)	2.0
UV ₂₅₄ (cm ⁻¹)	0.050
Bromide (µg/L)	71

Ammonia (mg/L)	0.30
Total Iron (mg/L)	1.3
Dissolved Iron (mg/L)	0.059
Total Manganese (mg/L)	0.064
Dissolved Manganese (mg/L)	0.012

¹ Analyses conducted by Eurofins Eaton Analytical

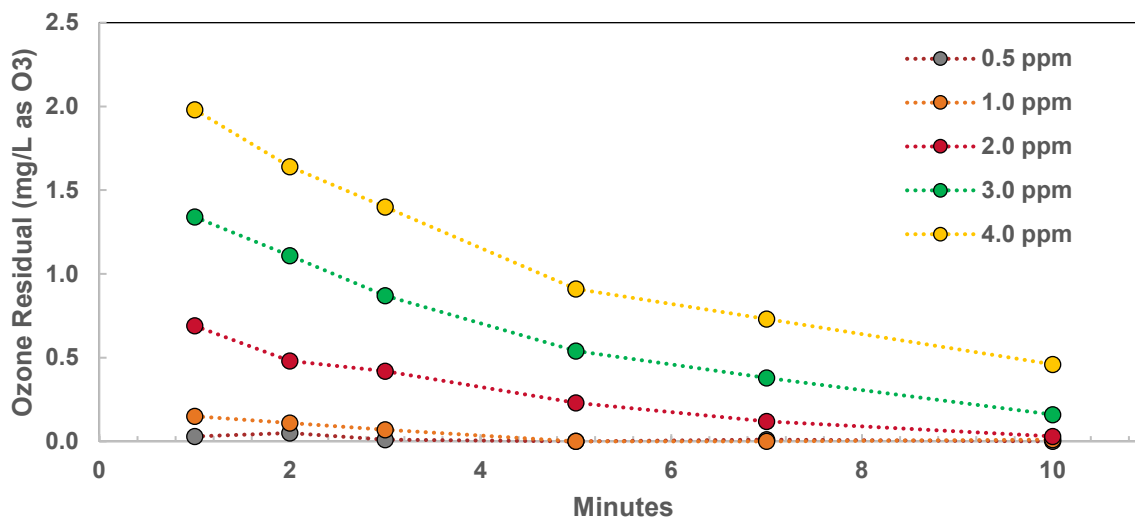


Figure 3-1: Ozone Decay Curves for Five Ozone Doses Tested

Figure 3-2 illustrates how TOC and dissolved UV₂₅₄ were reduced during bench-scale ozone testing. Both parameters reduced with increased ozone doses. TOC was reduced by up to 0.3 ppm, which is a relatively small decrease. Ozone does not typically reduce TOC but alters it such that it reduces UV absorbance and aromaticity. The UV₂₅₄ signal was reduced by a more significant amount, from 0.05 to 0.02 cm⁻¹. This reduction reflects the changing nature of the organics after ozonation, as pi bonds in aromatic constituents are reduced. As part of method SM5910, samples are filtered prior to UV analysis to control particle-related variations in UV absorbance. Some of the subsequent pilot data was not filtered prior to UV analysis, which accounts for the lower UV absorbance values noted in the bench-scale study.

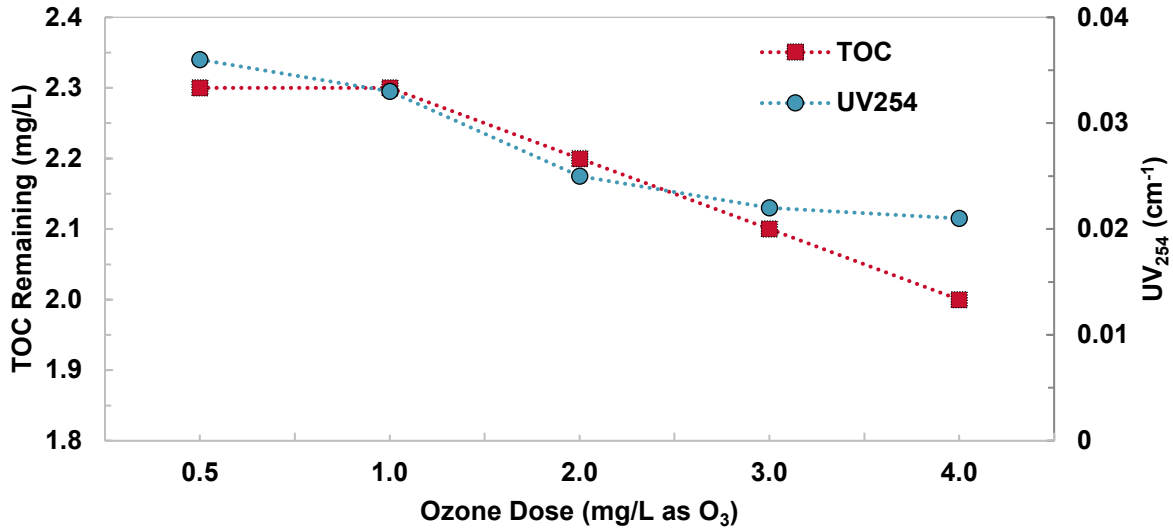


Figure 3-2: TOC and Dissolved UV₂₅₄ Values for the Five Ozone Doses Tested

Figure 3-3 illustrates the increase in bromate formation with increasing ozone doses. Bromate formation was 9.9 µg/L at an ozone dose of 3.0 mg/L and 17 µg/L at an ozone dose of 4.0 mg/L. Considering the federal MCL of 10 µg/L for bromate, ozone doses approaching 3.0 mg/L can be problematic with the bromide level present during testing (i.e., 71 µg/L). There are several strategies to reduce bromate formation if a higher ozone dose is needed to achieve treatment targets.

Based on these bench-scale ozone testing results, an ozone dose of 1.6 mg/L was chosen as the baseline for pilot-scale operation to maintain a ratio of ozone to settled water TOC of 1. This ratio was chosen based on results from the bench-scale testing at varying ozone doses to avoid bromate formation above the MCL. An ozone dose of 1.6 mg/L will help to avoid bromate formation and maximize UV₂₅₄ reduction.

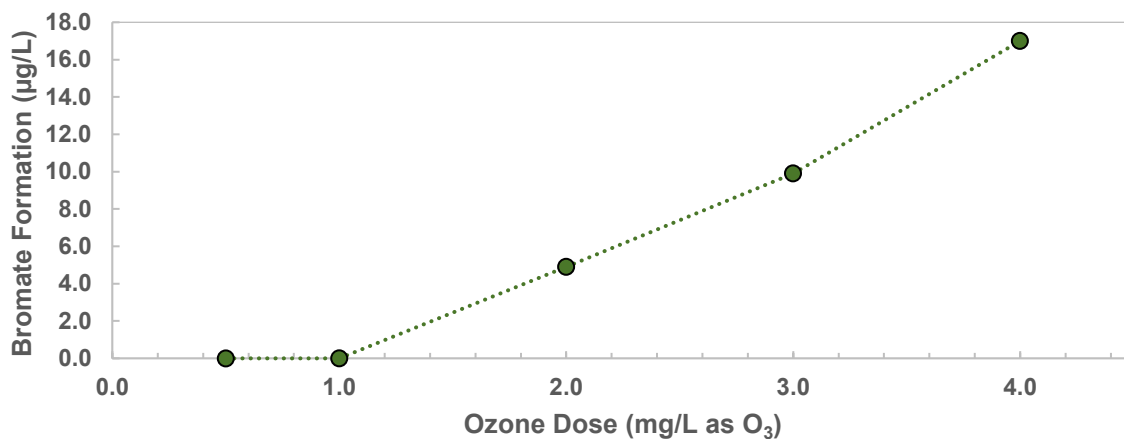


Figure 3-3: Bromate Concentrations for the Five Ozone Doses Tested

3.3 GAC Isotherm and Simulated Distribution System Testing

Phase II of the bench-scale study tested the effectiveness of three (3) GAC medias to reduce TOC and UV₂₅₄ in post-filtration water. Raw water and GAC-treated water were used to develop data for a range of TOC concentrations. These samples underwent 7-day SDS testing with free chlorine to examine the potential for DBPs to form across a range of TOC values and to determine the relationship between these two parameters. The 7-day period was chosen based on the distribution system modeling conducted by HDR. There is 1-day of detention time within the finished water transmission main piping between the WTP and West Ash Pump Station. The modeling indicated that the average water age in the distribution system storage tanks ranged from 3 to 9 days and winter water age ranged from 4 to 13 days. The 7-day incubation was selected as the value that was representative of the typical water age within the distribution system.

3.3.1 Initial Water Quality Characterization

Table 3-4 lists the water quality parameters measured for the source water upon arrival at the HDR's Water Quality Laboratory.

Table 3-4: Pre-Isotherm Testing, Source Water Characterization

Water Quality Parameter ¹	Laboratory Method
TOC	SM5310C/E415.3
UV ₂₅₄	SM5910

¹ Analyses conducted by Eurofins Eaton Analytical

Isotherm testing was conducted according to the following procedures.

1. Post-primary water was filtered to mimic post-filtration water at the full-scale (without disinfectant added)
 2. A two-stage system of 2.7 µm followed by 0.7 µm filtration was conducted with glass fiber filters
 3. Filtered samples were placed in 2L glass amber bottles (reactors)
 4. GAC carbon samples were ground to less than 325 standard mesh size and added to the 2L reactors at the following carbon concentrations: 2.5, 5, 10, 20, 50 mg/L
 5. Isotherm reactors were then placed on an orbital table that was set to gently shake at room temperature for 7 days
 6. Following the 7-day isotherm testing, samples were filtered at 0.7 µm to remove GAC and then sampled for TOC and UV₂₅₄ (see Table 3-5).

Table 3-5: Isotherm Testing Analytics

Water Quality Parameter ¹	Laboratory Method
TOC	SM5310C/E415.3
UV ₂₅₄	SM5910

¹ Analyses conducted by Eurofins Eaton Analytical

Sample waters from GAC testing then underwent SDS testing according to the following procedures.

1. The filtered isotherm samples were placed in 500 mL glass amber bottles (reactors) with GAC concentrations of 2.5, 10, and 50 mg/L
2. Additional SDS reactors were made for raw water as well as the post-filtration water without GAC treatment²
3. 125mL glass amber bottles were used to conduct overnight and multi-day chlorine demand tests; data from these demand tests was used to estimate 7-day chlorine demand
4. Following chlorine demand tests, the 500 mL reactors were dosed with sodium hypochlorite at three concentrations to target a 7-day free chlorine residual of 1.0 mg/L
5. The SDS reactors were held in a circulating water bath at 25°C for 7 days to mimic greater-than-average temperatures and durations in the distribution system
6. Additional reactors were made for the 10 mg/L GAC-treated samples, and held for 15 days to mimic maximum residency in the distribution system
7. At 7 days (or 15 days) samples were pulled and tested for free chlorine residuals; samples with free chlorine close to 1 mg/L were then tested for TTHM and HAA5 (see Table 3-6)

Table 3-6: SDS Testing Analytics

Water Quality Parameter ¹	Laboratory Method
HAA5	SM6251B
TTHM	EPA551.1

¹ Analyses conducted by Eurofins Eaton Analytical

3.3.2 GAC Testing Results and Media Selection

GAC isotherm testing provided TOC and dissolved UV₂₅₄ data to inform the media selection for pilot-scale testing. The “q-value” (adsorption capacity) was calculated based on the data. The calculation is as follows:

$$\text{q-value} = [\text{TOC initial (mg/L)} - \text{TOC final (mg/L)}] / [\text{GAC conc. (mg/L)}] * 1000$$

Greater q-values indicate that more TOC was removed and illustrate the GAC media that are more effective at reducing TOC. Figure 3-4 depicts the q-values and corresponding TOC concentrations

² The “post-filtration” water was sampled post-primary and filtered in the lab to mimic post-filtration water without prior disinfectant addition

across the three (3) GAC media tested. Carbon Central LLC (CCL) and Carbon Activated Corp. COL-60 (CA-60) both underperformed in comparison to Calgon Filtrasorb 400 (F-400). This finding was further substantiated by dissolved UV₂₅₄ data (see Figure 3-5). F-400 carbon had a similar removal profile to CA-60 but the overall data suggests that F-400 is best at removing DBP precursors.

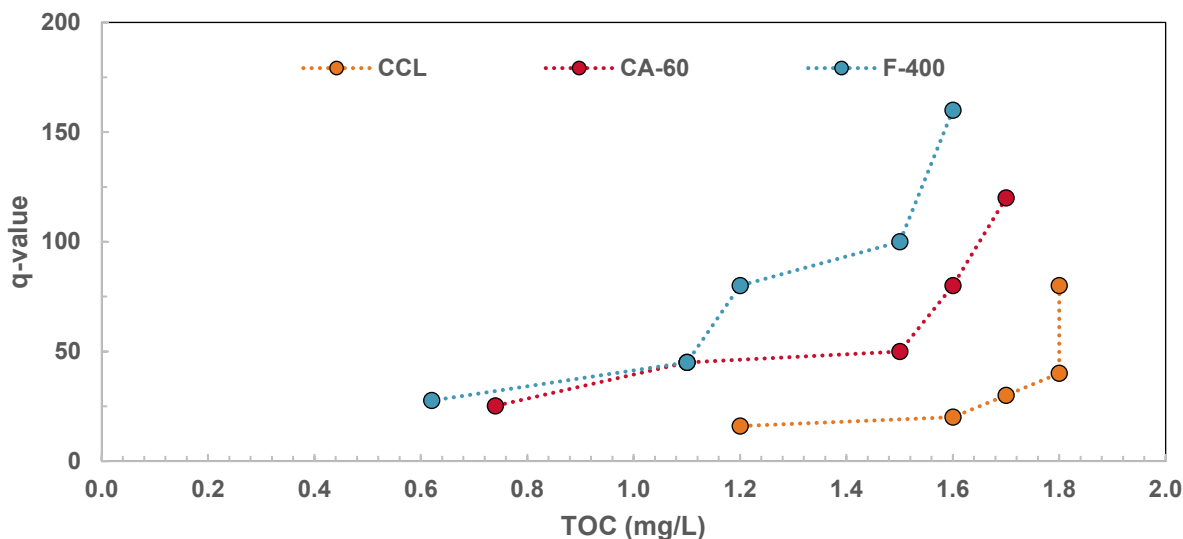


Figure 3-4: q-Values for the Three GAC Tested

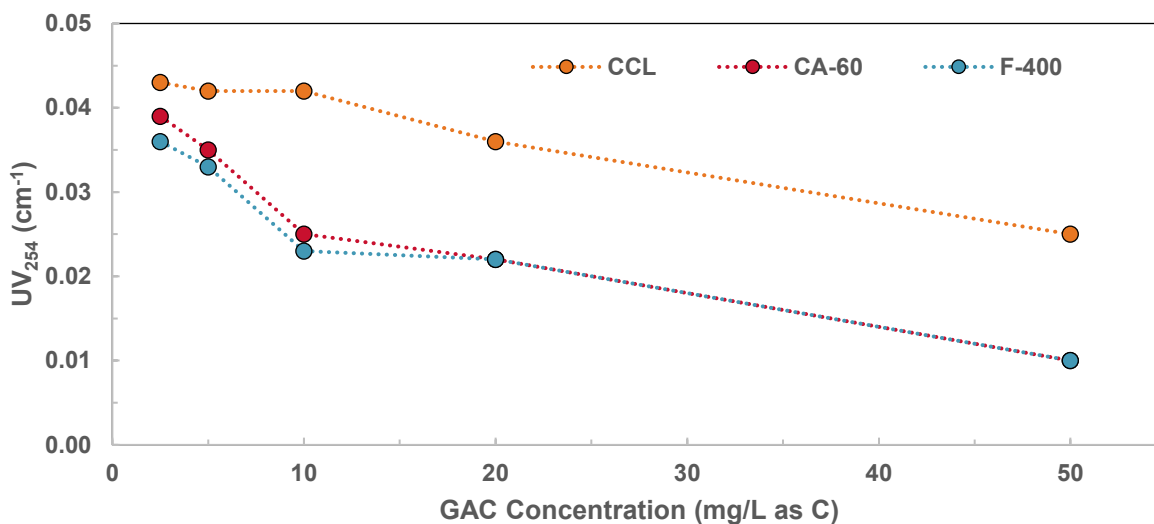


Figure 3-5: UV₂₅₄ Values for the Three GAC Tested

Further SDS testing was performed to verify DBP formation across the three (3) GAC medias. Figure 3-6 illustrates a comparison of TOC concentration from samples generated with GAC testing versus DBP formation after 7-days of SDS testing. This correlation is useful in targeting overall TOC reduction to meet TTHM and HAA5 targets. From the data provided, TTHMs are the limiting group of contaminants with an MCL of 80 µg/L, as compared to 60 µg/L for HAA5. If TOC were to be targeted to achieve between 80 to 100 percent of the TTHM MCL, then TOC target range of approximately 1.0 to 1.2 mg/L will need to be achieved under the current testing conditions, respectively.

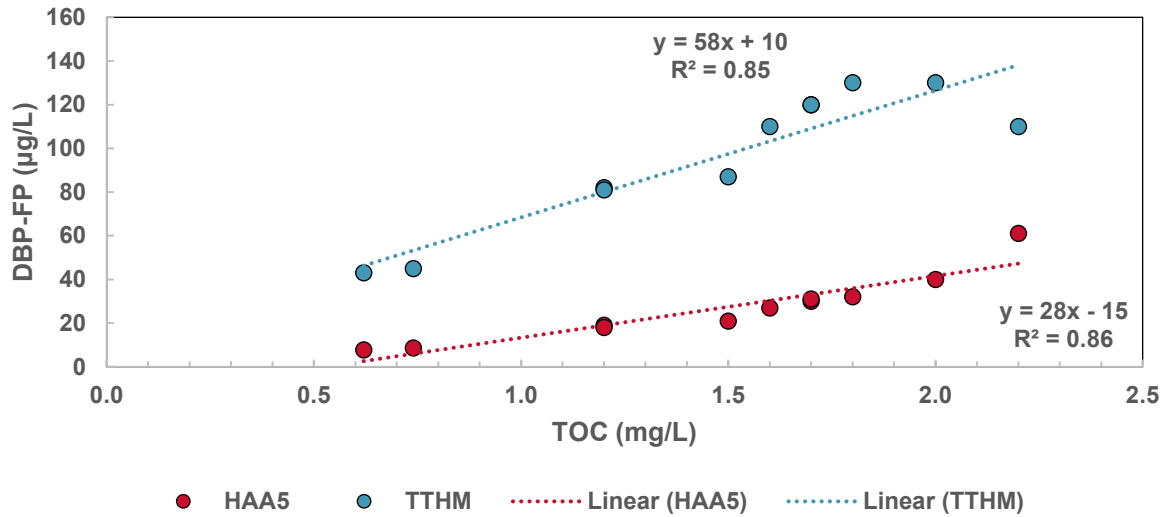


Figure 3-6: TOC Concentration from GAC Testing vs. DBP-FP after 7-days of SDS Testing (temp = 25°C, pH = ambient)

Figure 3-7 and Figure 3-8 illustrate TTHM and HAA5 formation after 7 days (7d) and 15 days (15d) of SDS testing across varying concentrations of the three (3) GAC medias tested. These figures further illustrate that F-400 outperformed the other two medias tested. F-400 was recommended for further pilot-scale testing.

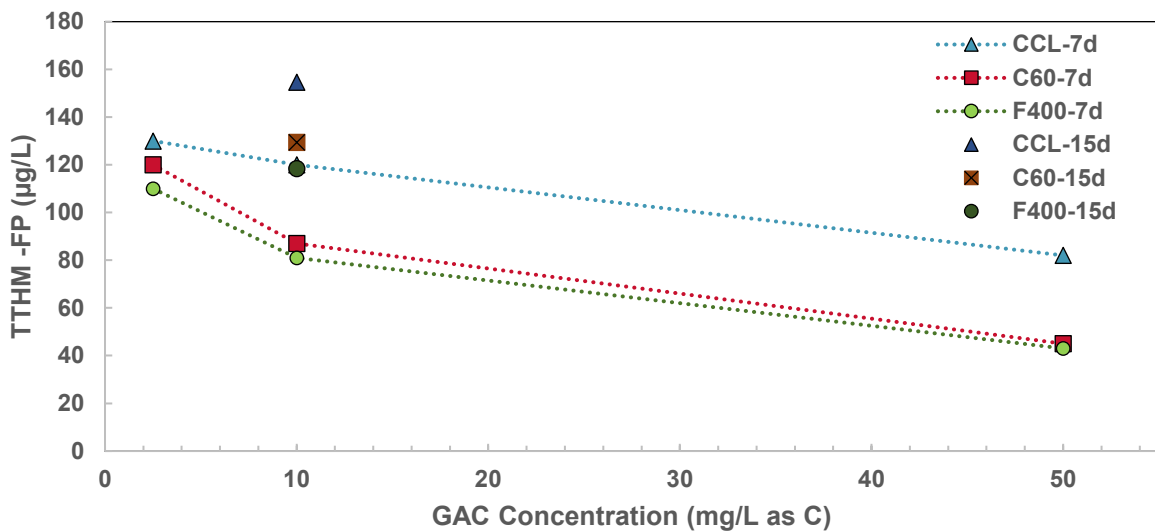


Figure 3-7: TTHM-FP over varying GAC Concentrations (7-days and 15-days of SDS Testing)

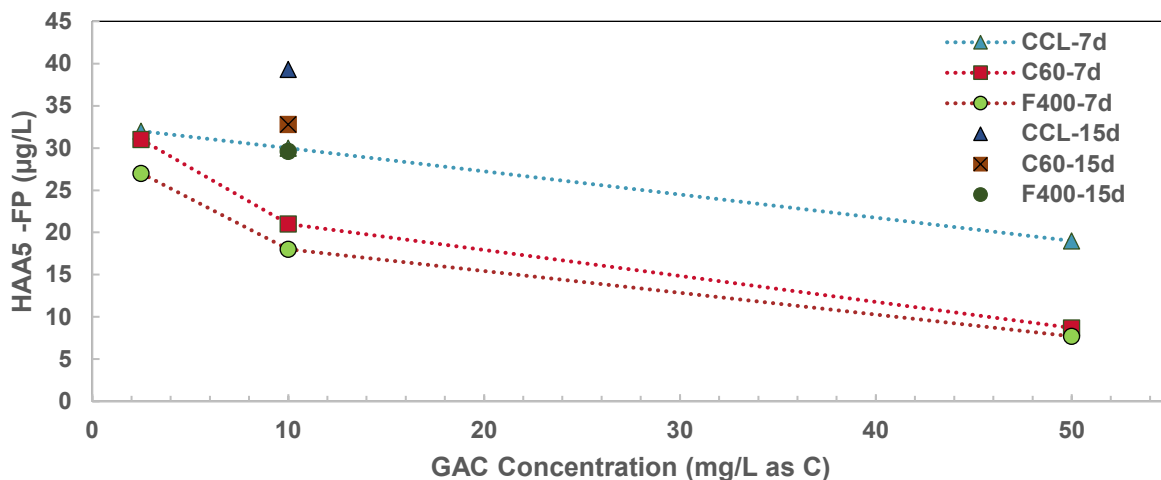


Figure 3-8: HAA5-FP over varying GAC Concentrations (7-days and 15-days of SDS Testing)

3.4 Air Stripping Testing

Phase III of the bench-scale testing included air stripping (aeration) to remove TTHMs from post-filtration water. SDS studies were conducted to simulate air stripping within the City's distribution system reservoirs to determine TTHM formation potential that can occur downstream of aeration.

3.4.1 Initial Water Quality Characterization

Table 3-7 lists the water quality parameters used to measure sample water prior to aeration testing.

Table 3-7: Pre-Aeration Testing, Source Water Characterization

Water Quality Parameter	Laboratory Method
pH	SM4500-HB
Alkalinity (mg/L as CaCO ₃)	SM2320
Chlorine residual	HACH, DPD method
TOC ¹	SM5310C/E415.3
Bromide ¹	EPA300

¹ Analyses conducted by Eurofins Eaton Analytical

Aeration testing was based on research by Brooke and Collins (2011) and conducted according to the following procedures.

1. Post-primary water was filtered to mimic post-filtration water at the full-scale (without disinfectant added).

2. A two-stage filtration system was conducted using glass fiber filters (2.7µm followed by 0.7µm).
3. Four filtered samples were placed in 3.7 L glass aeration reactors with glass, stainless steel, and polytetrafluoroethylene parts.
4. Air was supplied to each aeration reactor via a portable, oil-free air compressor, with airflow rates controlled by 5 L/min (max) flow meters.
5. Aeration studies were run at room temperature.
6. Four fine-bubble diffuser stones were plumbed into the bottom of each reactor.
7. Two holes were drilled into the stainless-steel lid of each reactor (14.3 cm in diameter). One hole was just large enough for the tubing to pump air into the reactors, and the other 0.5 cm hole was drilled for air to escape and transfer vapor phase TTHMs out of the reactor. This simulated full-scale aeration, which requires headspace removal via forced air ventilation. One reactor had an additional three holes (four in total) drilled for air to escape. This provided a comparison of stripping potential with a greater driving force across the vapor phase.
8. TTHMs testing was performed in aeration reactors that included a 3 mg/L dose of chlorine. The reactors are held at room temperature for 24 hours to simulate the average time from the WTP to West Ash PS, including residence time in the PS.
9. After 24 hours, the air compressor was used to run the flow conditions specified in Table 3-8.

Table 3-8: Flow Conditions in Aeration Reactors

Airflow Rate (L/min)	Time (min)	Air-to-Water Ratio	No. of 0.5cm Venting Holes in Lid
0 (control)	0	N/A	N/A
1.5	45	22.5:1	1
1.5	60	30:1	1
1.5	60	30:1	4
3	45	45:1	1
3	60	60:1	1

Following completion of the aeration tests, TTHM samples were collected in 60-mL glass sample vials with preservative. Care was taken to minimally disturb/aerate the samples.

Table 3-9 lists the analytics conducted on aerated samples.

Table 3-9: Aeration Testing Analytics

Water Quality Parameter	Laboratory Method
pH	SM4500-HB
Chlorine residual	HACH, DPD method
TOC ¹	SM5310C/E415.3
TTHM ¹	EPA551.1

¹ Measurements conducted by Eurofins Eaton Analytical, Monrovia, CA

SDS testing was conducted following aeration testing. Aerated samples were partitioned into 500 mL amber glass bottles and dosed with sodium hypochlorite, following the same procedures outlined in Section 2.2.

After 6 days of SDS reaction time (7 days total free chlorine exposure including the 24 hours of pre-aeration chlorine contact time), TTHM samples were pulled from the SDS reactors with the closest residual to 1 mg/L as free chlorine.

3.4.2 Air Stripping

An initial source water characterization was performed prior to running aeration tests. Post-primary sample water was shipped overnight to HDR's Water Quality Laboratory and then filtered to mimic post-filtration water that had not previously been chlorinated. Filtered samples were then tested for the parameters outlined in Table 3-10.

Table 3-10: Pre-Aeration Testing, Source Water Characterization

Water Quality Parameter	Analytical Value
pH	8.2
Alkalinity (mg/L as CaCO ₃)	160
Chlorine residual (mg/L as Cl ₂)	ND
TOC (mg/L as C)	2.7
Bromide (µg/L)	70

A 3 mg/L dose of chlorine was added to the samples 24 hours prior to aeration testing. Aeration tests were conducted according to the flow conditions outlined in Table 3-8.

Figure 3-9 illustrates that 24 hours of chlorine contact (using a 3 mg/L dose of chlorine) resulted in similar TTHM concentrations across the 5 reactors prior to aeration. Roughly 25 µg/L of TTHMs were formed from 24 hours of exposure, with the various TTHM species formed in a similar profile (see Figure 3-9). After 45 to 60 minutes of aeration at various flow rates, the TTHM concentrations were reduced from 8 µg/L for the lowest air-to-water ratio, down to less than 1 µg/L for the highest air-to-water ratio (see Figure 3-10).

7-day SDS trials were performed on aerated samples to examine how TTHM precursors were affected by aeration and to examine what might ultimately happen in the distribution system with more time

exposed to free chlorine.³ Figure 3-11 illustrates that TTHM formation was uniformly around 100 µg/L after six further days of chlorination, regardless of how effectively TTHMs were stripped after the first 24 hours (Figure 3-10). It is evident that TTHM formation was slow within the first 24 hours of chlorination and that TTHM continued to form in significant quantities after air stripping.

Though excellent reduction in TTHMs was observed with aeration, 24 hours of chlorine contact resulted in relatively slow TTHM formation and allowed for additional TTHM formation in the six-day incubation period. For full-scale implementation, the aeration would be installed within the distribution system pump station reservoirs. The air stripping results indicated that aeration within the reservoirs would adequately remove TTHMs formed upstream of the reservoirs. However, due to the slow formation of the TTHMs, air stripping would not adequately remove TTHMs formed downstream of the reservoirs. Therefore, aeration does not appear to be an effective option for full-scale implementation based on the current treated water quality. Aeration may be considered in the future depending on the TOC removal once the full-scale improvements are implemented

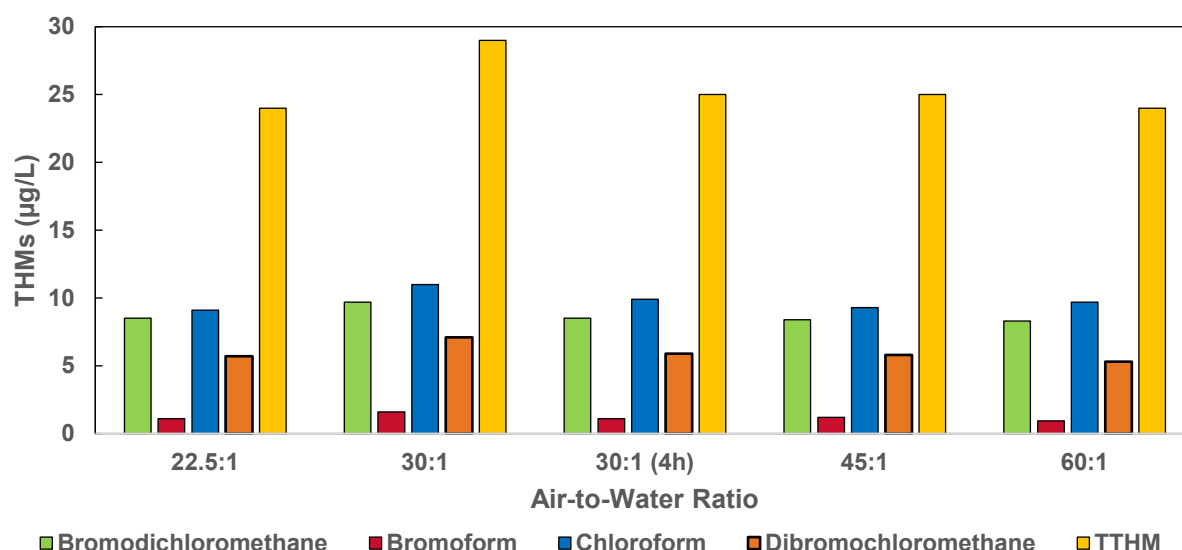


Figure 3-9: Trihalomethane Concentrations Prior to Aeration (4h indicates the reactor with 4 venting holes)

³ While samples had already been chlorinated for 24 hours, they were only chlorinated for a further six days to generate a total of seven days of chlorination.

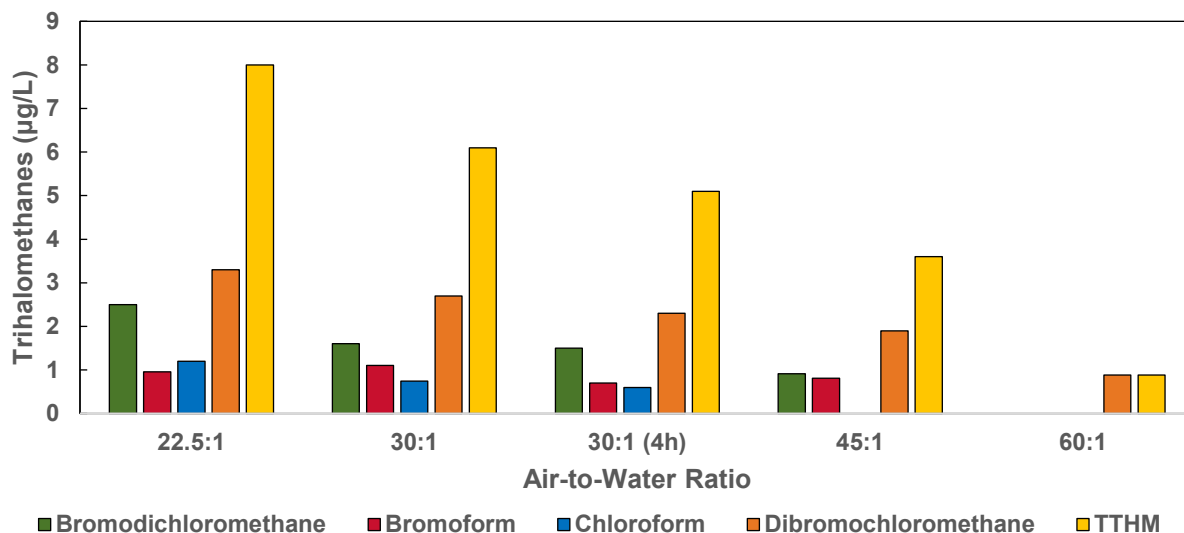


Figure 3-10: Trihalomethane Concentrations After Aeration (4h indicates the reactor with 4 venting holes)

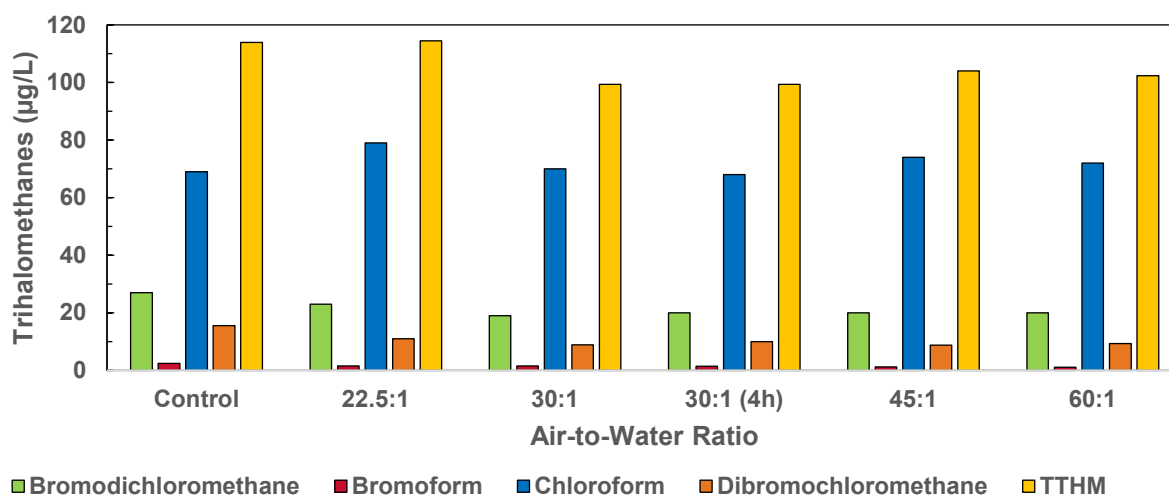


Figure 3-11: Trihalomethane Concentrations After 7-Days of SDS Testing (4h indicates the reactor with 4 venting holes)

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4 Pilot-scale Testing

4.1 Objectives

Pilot-scale testing (pilot) was conducted for six (6) months on post-secondary/filter influent and filter effluent to evaluate the treatment technologies capable of enhanced TOC removal and reduced DBP formation to provide the opportunity to convert to free chlorine for secondary disinfection. The pilot objectives are to:

- Determine a target TOC concentration to achieve TTHM and HAA5 targets with free chlorine as secondary disinfection.
- Compare effectiveness of treatment technologies for improving TOC removal and reducing DBP formation potential (DBP-FP) using SDS testing.
- Recommend most-effective treatment alternative for future consideration.

The following three (3) treatment schemes were piloted.

1. Ozone/Biofiltration: Post-softening ozonation followed by biologically active filtration (BAF) with pre-exhausted GAC.

Ozone is a powerful oxidant that helps mitigate taste and odor causing compounds, color, TOC, chlorine DBP precursors, and constituents of emerging concern (CEC), such as pharmaceuticals and personal care products. Ozone can also oxidize metals, such as iron and manganese. Ozone is a powerful disinfectant and can achieve inactivation of bacteria, viruses, and protozoa, provided there is an adequate ozone dose and adequate contact time. In addition, the ozone's oxidative power breaks down complex, large chain organics into smaller, more basic compounds that are easily consumed by microorganisms. Ozone is typically combined with a downstream biological treatment step, like BAF, to remove these easily degradable organic compounds and minimize distribution system regrowth potential. A biofilter operates without the presence of a disinfectant residual, allowing for naturally occurring bacteria to colonize filter media. These organisms actively degrade organic compounds and other contaminants, as shown in Figure 4-1. Biodegradation coupled with particle removal via filtration make BAF an effective solution for turbidity and supplemental TOC removal. BAF media is typically comprised of sand, anthracite, and/or GAC. Relative to other media, GAC improves BAF implementation by providing additional treatment through adsorption during startup and the initial months of operation. It also provides greater surface area for bacteria to colonize. However, biodegradation becomes the predominant removal mechanism once the GAC reaches equilibrium, also known as effective exhaustion. Installed GAC media can provide robust BAF treatment for 10 or more years without requiring replacement.

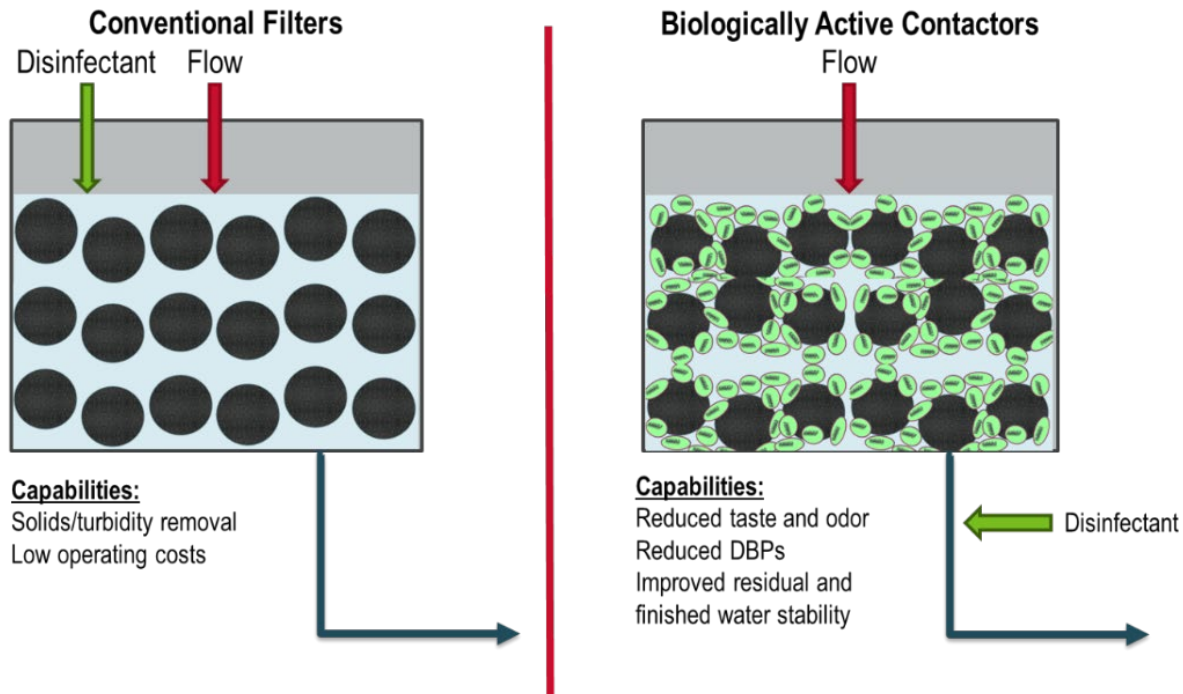


Figure 4-1: Conventional Filters vs. Biologically Active Filters

2. GAC Filter Adsorber: Post-softening ozonation followed by GAC filter adsorbers (sand filter with virgin GAC media cap).

A filter adsorber consists of GAC media and uses GAC adsorption for turbidity and contaminant removal. Secondary effluent with ozonation was the source water for this alternative. The GAC filter adsorber had a media configuration and operation similar to BAF but utilizes virgin media. The virgin media can be changed out when certain contaminants such as TOC or CECs reach breakthrough or transition to biofiltration using the spent media. A GAC adsorber can provide the combined benefits of biofiltration and adsorption. Depending on the media change-out frequency, it can also prove to be a cost-effective alternative while still providing robust treatment for TOCs and DBPs removal.

3. GAC Contactor: Post-filtration GAC contactors with virgin GAC media.

A post-filtration GAC contactor provides additional contaminant removal through adsorption on active carbon media. The GAC contactor can serve as a polishing step for organic compound removal, including low molecular weight hydrophobic organic compounds, such as some DBP precursors (Cuthbertson et al. 2019). GAC is also effective at removing many CECs including per- and polyfluoroalkyl substances (PFAS). However, this adsorptive capacity decreases over time as the active sites become exhausted. This requires regular GAC replacement to maintain treatment effectiveness. The frequency of GAC media change-out is an important factor in assessing operation and maintenance cost feasibility.

4.2 Pilot Setup

Pilot-scale units were provided by Intuitech Inc including one (1) ozone skid and one (1) filter skid with four (4) filter columns (see Figure 4-2). The packaged units were equipped with the necessary pumps, blowers, tanks, ozone generators and analyzers, and sensors. To provide consistent flow and water pressure on the pilot skids, break tanks were used to feed all treatment trains. Figure 4-3 shows the process flow diagram for all three (3) treatment trains.

Pilot 1 – Ozone with BAF

Ozone effluent was fed into two BAF columns operating in parallel at a 5-minute empty bed contact time (EBCT). Exhausted GAC media from a nearby full-scale operational treatment plant was added to both BAF columns. Low levels of nutrients (orthophosphate and ammonia) were added to the BAF 2 influent in the optimization phase to improve TOC removal.

Pilot 2 – Ozone with GAC adsorber

Virgin GAC media (Filtrisorb 820) was used in filter adsorber 1 with 5-minute EBCT and received ozonated water. During the optimization phase, BAF 1 was converted to filter adsorber 2 to compare the effluent water quality between new and exhausted filter adsorbers.

Pilot 3 – GAC contactor

The GAC contactor (20-minute EBCT) was fed from existing WTP conventional filters and contained virgin GAC media (Filtrisorb 400).



Figure 4-2: Intuitech pilot filter skid (left) and ozone skid (right)

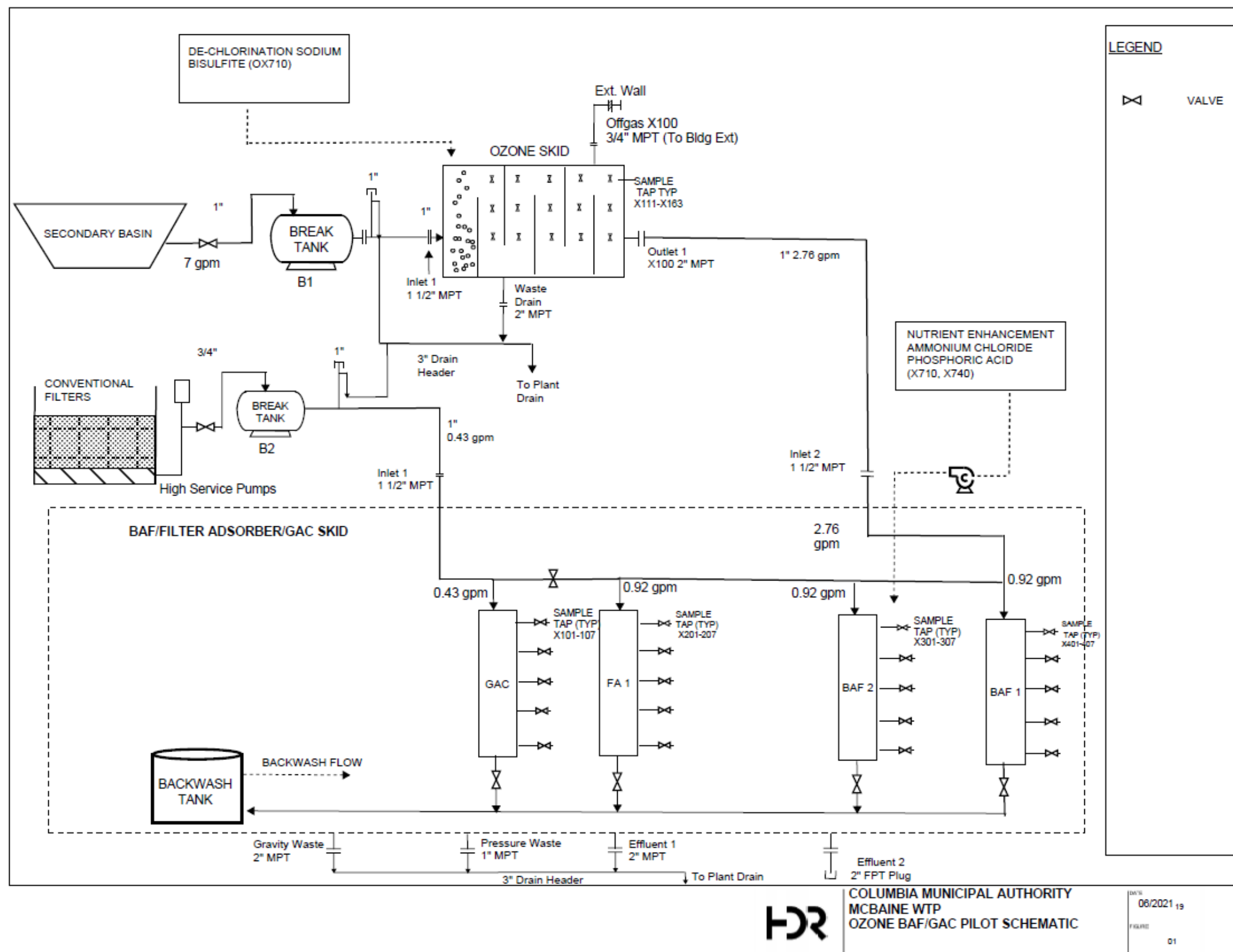


Figure 4-3: Process Flow Diagram for Pilot Treatment Trains

4.3 Source Water Quality

Two different source waters were used for two separate pilot treatment processes: full-scale softening effluent and full-scale filter effluent. The quality of the source waters is summarized in Table 4-1. Since secondary effluent has chlorine residual, it was dechlorinated using sodium thiosulfate.

Temperature measurements were collected on the full-scale softening effluent to verify BAF feasibility and filter adsorber operation. Bromide analysis was conducted on the full-scale softening effluent to determine bromate formation potential during ozonation.

Table 4-1: Source water quality (Average and range of data over 6-month pilot duration)

Parameter	Units	Softening Effluent/ Ozone Influent	Filter Effluent/ GAC Influent
pH	s.u.	8.6±0.1	8.5±0.1
Temperature	°C	14.7±0.4	—
Turbidity	NTU	13.5±4.4	2.8±3.2
Alkalinity	mg/L	158±10	157.2±11.2
TOC	mg/L	1.8±0.2	1.7±0.1
DOC	mg/L	1.7±0.2	1.7±0.2
UV ₂₅₄ (TOC) ¹	cm ⁻¹	0.11±0.01	0.05±0.01
UV ₂₅₄ (DOC) ²	cm ⁻¹	0.06±0.01	0.04±0.01
HAA5 ³	µg/L	7.9±1.5	9.6±1.5
TTHM ³	µg/L	23.4±2.7	35.7±32.3
Bromide	µg/L	30.5±12.7	—
Manganese (Total)	mg/L	0.12±0.03	0.07±0.03
Manganese (Dissolved)	mg/L	0.05±0.03	0.04±0.02
Iron (Total)	mg/L	1.1±0.12	0.22±0.13
Iron (Dissolved)	mg/L	0.31±0.08	0.12±0.07
Total Magnesium Hardness	mg/L	90	82
Total Calcium Hardness	mg/L	82	86

¹ UV₂₅₄ (TOC) refers to UV absorbance of sample without filtration.

² UV₂₅₄ (DOC) refers to UV absorbance of sample after filtration by 0.45 µm filter.

³ TTHM and HAA5 concentrations represent instantaneous measurements (not formation potential).

4.4 Testing Conditions and Operational Phases

The pilot test conditions and operational phases are summarized in Table 4-2 and Table 4-3, respectively.

Table 4-2: Pilot Test Conditions

Test Column	Media	Media Depth (inches)	Sand Depth (inches)	ES (mm)	Uniformity Coefficient
BAF 1	Exhausted GAC ¹	40	8	1.2-1.4	<1.4
BAF 2	Exhausted GAC ¹	40	8	1.2-1.4	<1.4
Filter Adsorber 1	Virgin Calgon ²	40	8	1-1.2	1.5
Filter Adsorber 2	Virgin Calgon ²	40	8	1-1.2	1.5
GAC Contactor	Virgin Calgon ³	72	-	0.55-0.75	1.9

1. Exhausted BAC media provide from Carbon Central LLC
2. Filtrasorb 820
3. Filtrasorb 400

Table 4-3: Pilot Operational Phases

Test Column	Baseline ¹ (Day 0 to Day 66)			Robustness ² (Day 67 to Day 100)			Optimization ³ (Day 95 to Day 176)				
	HLR (gpm/SF)	EBCT (min)	O ₃ TOC Ratio	HLR (gpm/SF)	EBCT (min)	O ₃ TOC Ratio	HLR (gpm/SF)	EBCT (min)	O ₃ TOC Ratio	Ammonia Dose (mg-N/L)	Ortho-P Dose (mg-P/L)
BAF 1	4.6	5.3	1	-	-	-	-	-	-	-	-
BAF 2	4.6	5.3	1	4.6	5.3	1.5	4.6	5.3	1	0.2	0.05
Filter Adsorber 1	4.6	5.3	1	4.6	5.3	1.5	1.3	20.4	1	-	-
Filter Adsorber 2	-	-	-	4.6	5.3	1.5	4.6	5.3	1	-	-
GAC Contactor	2.2	20.4	-	2.2	20.4	-	2.2	20.4	-	-	-

1. Baseline Condition: Steady state operation from 11/09/2020 to 01/14/2021 (Day 0 to Day 66)
2. Robustness Condition: Ozone challenge testing from 01/15/2021 to 02/17/2021 (Day 67 to Day 100)
3. Optimization Condition:
 - a. Nutrient enhancement from 02/12/2021 to 05/04/2021 (Day 95 to Day 176)
 - b. Increased EBCT from 04/13/2021 to 05/04/2021 (Day 155 to Day 176)

4.5 Data Collection and Monitoring

Data collection and water quality monitoring was conducted for the duration of the pilot (November 2020 to May 2021) according to the sampling plans provided in Table 4-4, Table 4-5, Table 4-6, and Table 4-7. Certain parameters were analyzed continuously from pilot skid equipment. Other parameters were collected as grab samples and analyzed by lab staff at either the McBaine WTP, Engineering Surveys & Services (ES&S, subconsultant of HDR), or at Eurofins Analytical (third-party lab).

Table 4-4: Water Quality Parameters (Pilot Skid)

Parameters	Sample Locations ¹	Number of Locations	Frequency
Flowrate	1,3,4,6,7	5	Continuous (on skid)
Ozone Dose	1	1	Continuous
Ozone Residual	X110 and X210 ²	2	Continuous
Turbidity	3,4,6,7	4	Continuous
Headloss	3,4,6,7	4	Continuous
Backwash Pressure	3,4,6,7	4	Continuous
Run Time	3,4,6,7	4	Continuous

1. Location 1 – Ozone Skid Influent, Location 2 – Ozone Skid Effluent/BAF Influent, Location 3 – BAF 1 Effluent, Location 4 – BAF 2 Effluent, Location 5 – GAC Contactor Influent, Location 6 – Filter Adsorber Effluent, Location 7 – GAC Contactor Effluent
2. Ozone Effluent Probes

Table 4-5: Water Quality Parameters (Analysis at McBaine WTP)

Parameters	Sample Locations ¹	Number of Locations	Frequency
Turbidity (grab)	1,2,3,4,5,6,7	7	Daily (1,2,5) 1 per week (3,4,6,7)
pH (grab)	1,3,4,5,6,7	6	1 per week
Dissolved Oxygen (grab)	1,2,3,4,5,6,7	7	1 per week
UV254	1,2,3,4,5,6,7	7	1 per week
Ozone Residual	X110 and X210 ²	2	3 per week
Alkalinity	1,2,3,4,5,6,7	7	1 per month
Temperature	1	1	1 per week
Total Calcium and Magnesium Hardness	1,5	2	Once at pilot initiation
Chlorine (Total and Free)	1,2,3,4,5,6,7	7	Once at pilot initiation
Chlorine (Total and Free)	1,5	2	1 per week
Chlorine Demand	2,3,4,6,7	5	1 per week
Iron (dissolved and total)	1,2,3,4,5,6,7	7	1 per week
Manganese (dissolved and total)	1,2,3,4,5,6,7	7	1 per week
HPCs	3,4,6	3	1 per month
Total and Fecal Coliforms	3,4,6	3	1 per month

1. Location 1 – Ozone Skid Influent, Location 2 – Ozone Skid Effluent/BAF Influent, Location 3 – BAF 1 Effluent, Location 4 – BAF 2 Effluent, Location 5 – GAC Contactor Influent, Location 6 – Filter Adsorber Effluent, Location 7 – GAC Contactor Effluent
2. Ozone Effluent Probes

Table 4-6: Water Quality Parameters (Analysis at Eurofins)

Parameters	Sample Locations ¹	Number of Locations	Total Samples per Location ²	Frequency ³	Sampling Methods
TOC ^{6,7,8,9}	1,2,3,4,5,6,7	7	9	1 per week	SM 5310C
TOC ^{6,7,8,9}	X102, X104, X106 ⁽⁴⁾	3	5	1 per 2 weeks	SM 5310C (UV254 at McBaine)
Dissolved Organic Carbon ^{4,6,7,8,9}	1,2,3,4,5,6,7	7	9	1 per week for 1 month	SM 5310C
DBPs (TTHM and HAA5) ^{6,7,8,9}	1,2,3,4,5,6,7	7	9	2 per month	EPA 524.2 and EPA 552.2
DBP-FP (TTHM and HAA5) ^{7,9}	1,2,3,4,5,6,7	7	9	2 per month	SM 5710C, SDS (chlorine)
DBP-FP (NDMA) ¹⁰	2,5,6,7			Total 3 sampling events	SM 5710C, SDS (chloramine)
Carboxylic Acids ⁷	1,2,3,4,6	5	7	1 per month	EEA SB RD100
Bromide ^{6,7}	1	1	3	2 per month	EPA 300.0
Bromate ^{6,7}	1,2	2	4	2 per month	EPA 317

1. Location 1 – Ozone Skid Influent, Location 2 – Ozone Skid Effluent/BAF Influent, Location 3 – BAF 1 Effluent, Location 4 – BAF 2 Effluent, Location 5 – GAC Contactor Influent, Location 6 – Filter Adsorber Effluent, Location 7 – GAC Contactor Effluent
2. Total includes blank and duplicate samples
3. Sampling frequency following Week 2 of pilot
4. DOC was dropped after 1 month of testing
5. GAC Contactor X102, X104, X106 (4, 9.5 and 15 min EBCT, respectively)
6. “Rush sample” results requested for Week 1 and Week 2 of pilot
7. Week 1 samples collected 11/12/2020
8. Week 2 samples collected 11/17/2020
9. Week 3 samples collected 11/19/2020
10. NDMA testing was also performed on WTP finished water and City of Columbia customer tap water

Table 4-7: Water Quality Parameters (Analysis at ES&S)

Parameters	Sample Locations ¹	Number of Locations	Total Samples per Location ²	Frequency ^{3,4}	Sampling Methods
Orthophosphate	2,3,4,6	4	6	1 per week for 2 weeks prior to dosing 1 per month upon dosing	SM 4500-P
Ammonia-Nitrogen	1,2,3,4,5,6,7	7	9	1 per week for 2 weeks	SM 4500-NH3
Nitrate-Nitrogen	1,2,3,4,5,6,7	7	9	1 per week for 2 weeks	SM 418D
Nitrite-Nitrogen	1,2,3,4,5,6,7	7	9	1 per week for 2 weeks	EPA 354.1

1. Location 1 – Ozone Skid Influent, Location 2 – Ozone Skid Effluent/BAF Influent, Location 3 – BAF 1 Effluent, Location 4 – BAF 2 Effluent, Location 5 – GAC Contactor Influent, Location 6 – Filter Adsorber Effluent, Location 7 – GAC Contactor Effluent
2. Total includes blank and duplicate samples
3. Sampling frequency following Week 2 of pilot
4. Week 1 samples collected 11/12/2020

4.6 Pilot Results

4.6.1 Correlation Plots and Treatment Targets

Correlations between DBPs and TOC and UV₂₅₄ absorbance were established using the data collected as part of this pilot. TOC and UV₂₅₄ absorbance can serve as surrogates for DBPs, such as TTHMs and HAA5. TOC and UV₂₅₄ absorbance can be simpler and more cost-effective to sample and analyze as compared to a DBP analysis. Specific treatment targets for TOC and UV₂₅₄ absorbance can be determined to maintain DBPs below the established MCLs or lower DBP levels depending on long-range water quality targets. Drinking water MCLs for TTHM and HAA5 are 80 µg/L and 60 µg/L, respectively. Many utilities set DBP targets at a specified percentage below the MCL (e.g., 80-percent of MCL). The City may elect to set DBP targets at current TTHM and HAA5 levels, which can result in significantly lower TOC targets. Developing this correlational analysis and establishing a framework for TOC and DBPs can be useful in optimal treatment selection and cost comparison of different treatment technologies. Correlations established between DBP formation potential (DBP-FP) and TOC and UV₂₅₄ for different pilot treatment processes are discussed below.

DBP-FP and TOC

Figure 4-4 and Figure 4-5 indicate a strong correlation between DBPs formed after the 7-day SDS test and TOC at all sampling locations, where an increase in TOC values results in an increase in TTHM and HAA5 formation. HAA5-FP was below the 60 µg/L MCL throughout the pilot duration for all treatment processes and thus is not a concern when switching final disinfection to free chlorine instead of chloramine. TTHM correlation indicates that effluent TOC concentrations between 1.0 to 1.2 mg/L can effectively result in TTHM concentrations between 80 and 100-percent of the MCL of 80 µg/L, respectively. Thus, a TOC target range of approximately 1.0 to 1.2 mg/L was established to evaluate the performance of each pilot treatment process.

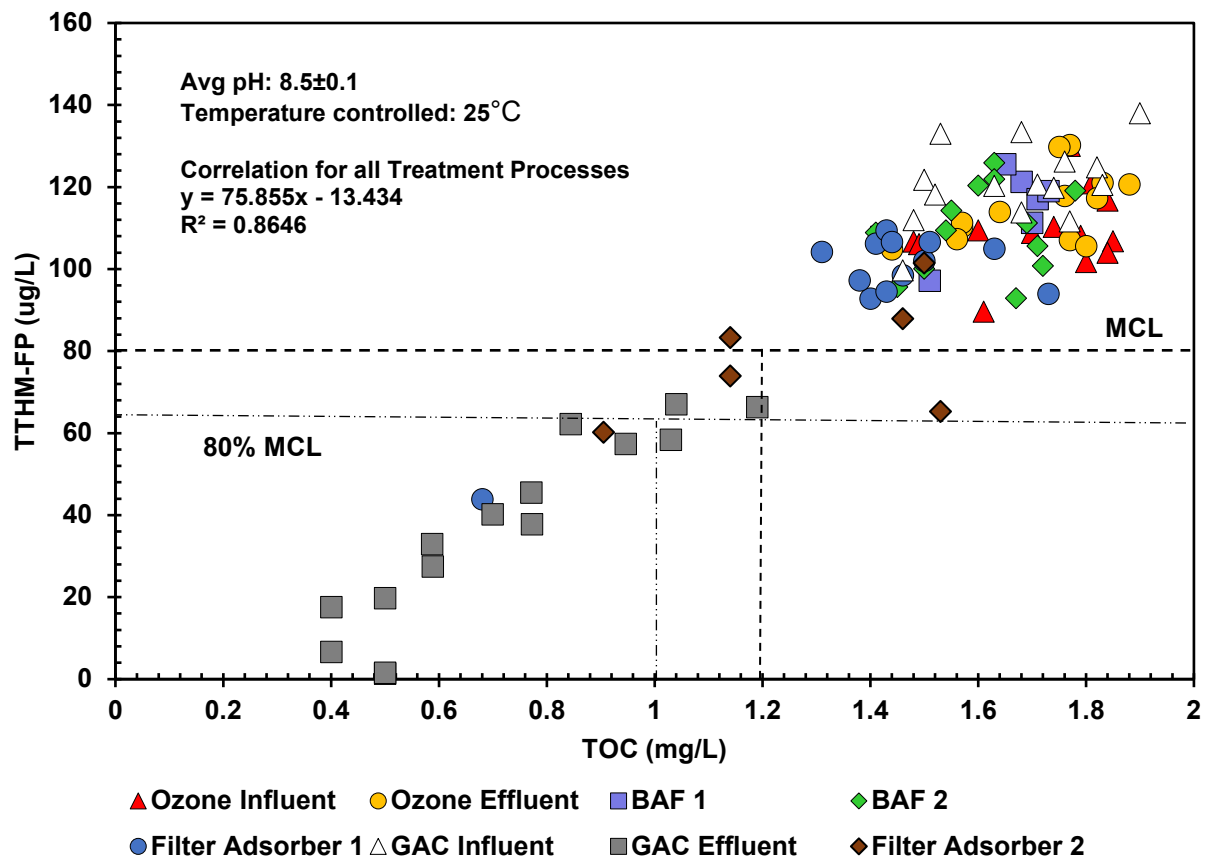


Figure 4-4: Correlation between TTHM-FP after 7-day SDS test and TOC concentrations for all treatment processes

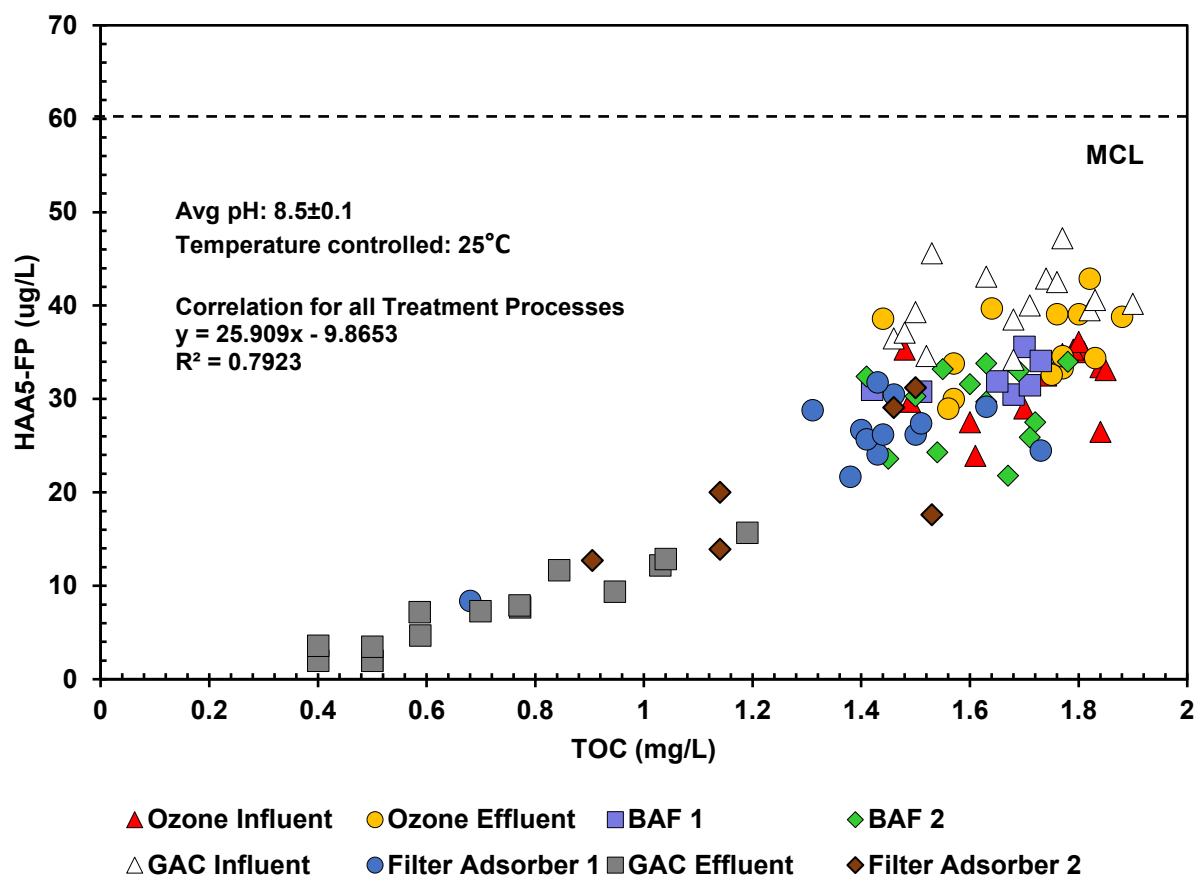


Figure 4-5: Correlation between HAA5-FP after 7-day SDS test and TOC concentrations for all treatment processes

UV₂₅₄ and TOC

There is a linear correlation between total UV₂₅₄ and TOC for BAF, filter adsorber, and GAC (Figure 4-6). However, the correlation is not strong for ozone influent, ozone effluent and GAC influent. Figure 4-6 also indicates the TOC levels below the target range of 1.0 to 1.2 mg/L were consistently achieved by the GAC contactor. A UV₂₅₄ absorbance range of 0.015 to 0.02 cm⁻¹ correlates well with a TOC range of 1.0 to 1.2 mg/L. Thus, a UV₂₅₄ absorbance of 0.015 to 0.02 cm⁻¹ was established as a target range for evaluating the performance of pilot treatment processes.

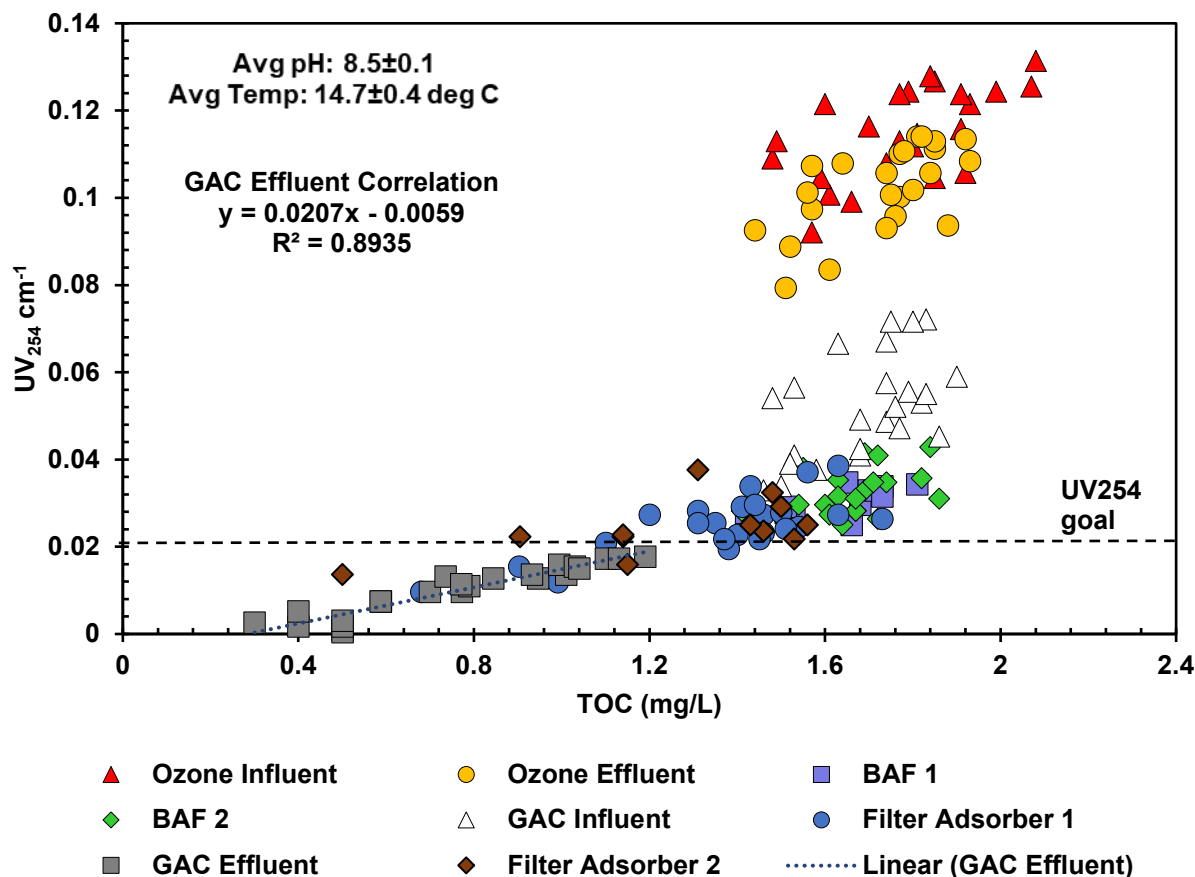


Figure 4-6: Correlation between UV₂₅₄(TOC) and TOC for each treatment process

DBP-FP and UV₂₅₄

Correlations between DBPs (TTHM and HAA5) and total UV₂₅₄ are shown in Figure 4-7 and Figure 4-8. As presented previously, all HAA5 SDS values were below 60 µg/L. There is a strong correlation for BAF, filter adsorber, and GAC TTHM SDS values and UV₂₅₄, where an increase in UV absorbance leads to an increase in TTHM formation. Figure 4-8 confirms that UV₂₅₄ absorbance below 0.02 cm⁻¹ is needed to consistently maintain TTHM SDS below 80 µg/L.

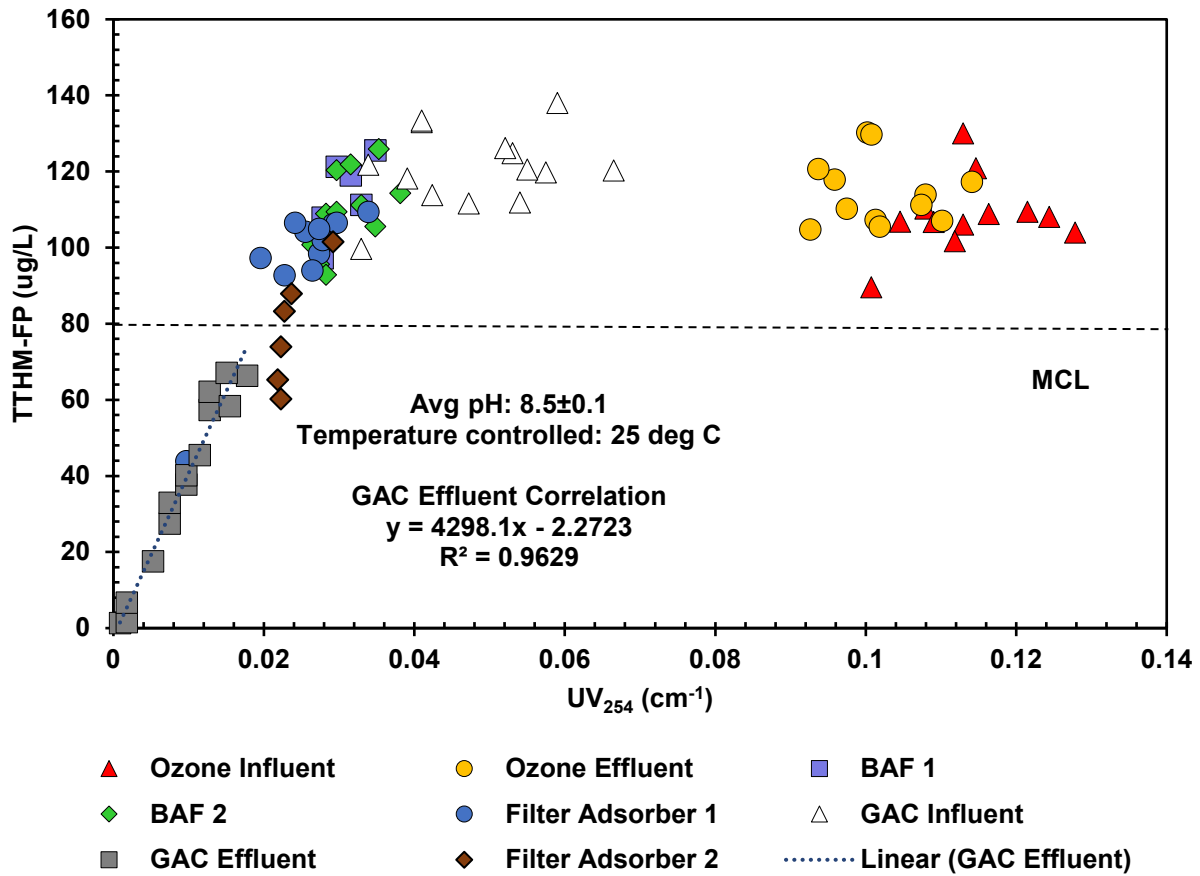


Figure 4-7: Correlation between TTHM-FP after 7-day SDS test and UV₂₅₄ for each treatment process

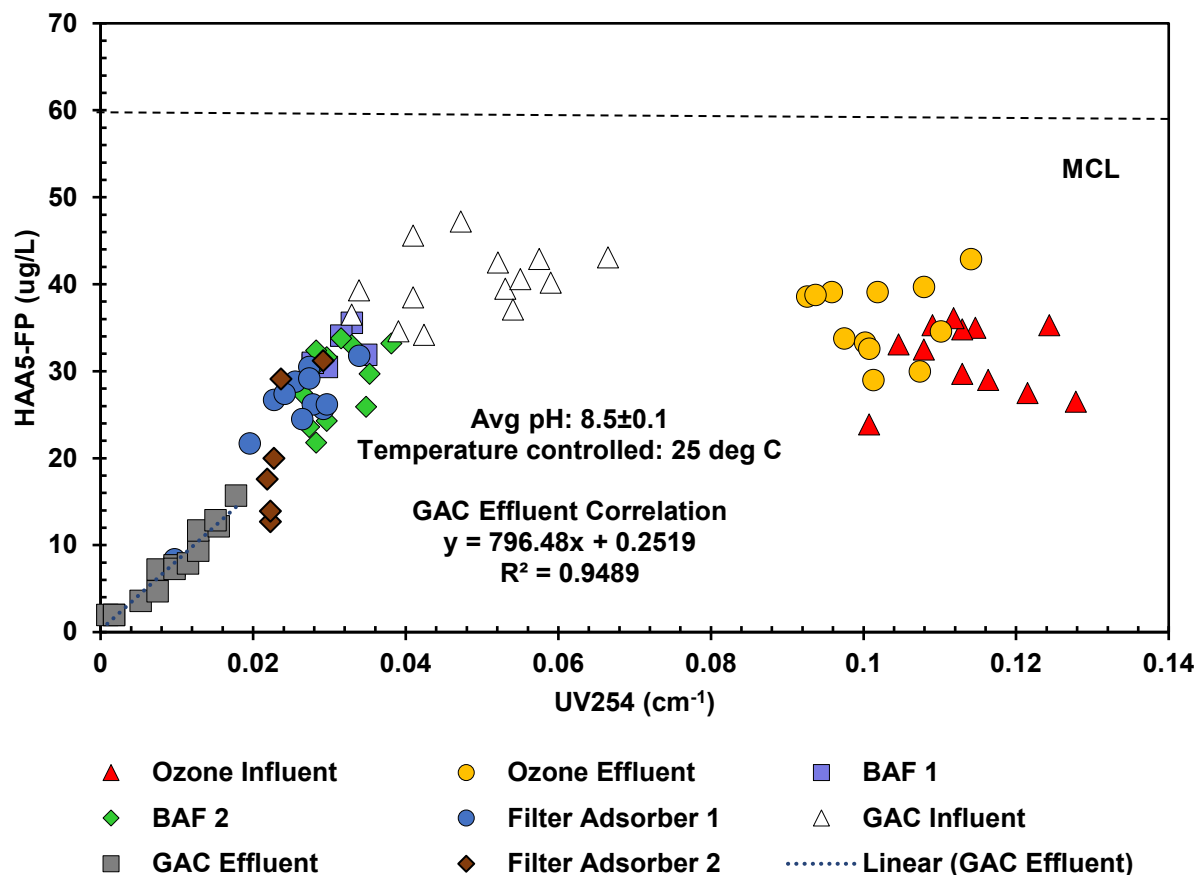


Figure 4-8: Correlation between HAA5-FP after 7-day SDS test and UV₂₅₄ absorbance for each treatment process

4.6.2 Total Organic Carbon Results

The average TOC data during different pilot phases and bed volumes (BV) is shown in Table 4-8 and Table 4-9. TOC values were below 1 mg/L consistently only in the GAC contactor. Filter adsorber TOC values were below the target range of 1.0 to 1.2 mg/L in the initial phase but continued to increase with pilot operation. Ozone and BAF TOC values continued to stay above 1.2 mg/L throughout the pilot operation.

Table 4-8: Average TOC Concentrations (Ozone, BAF and Filter Adsorber Effluent)

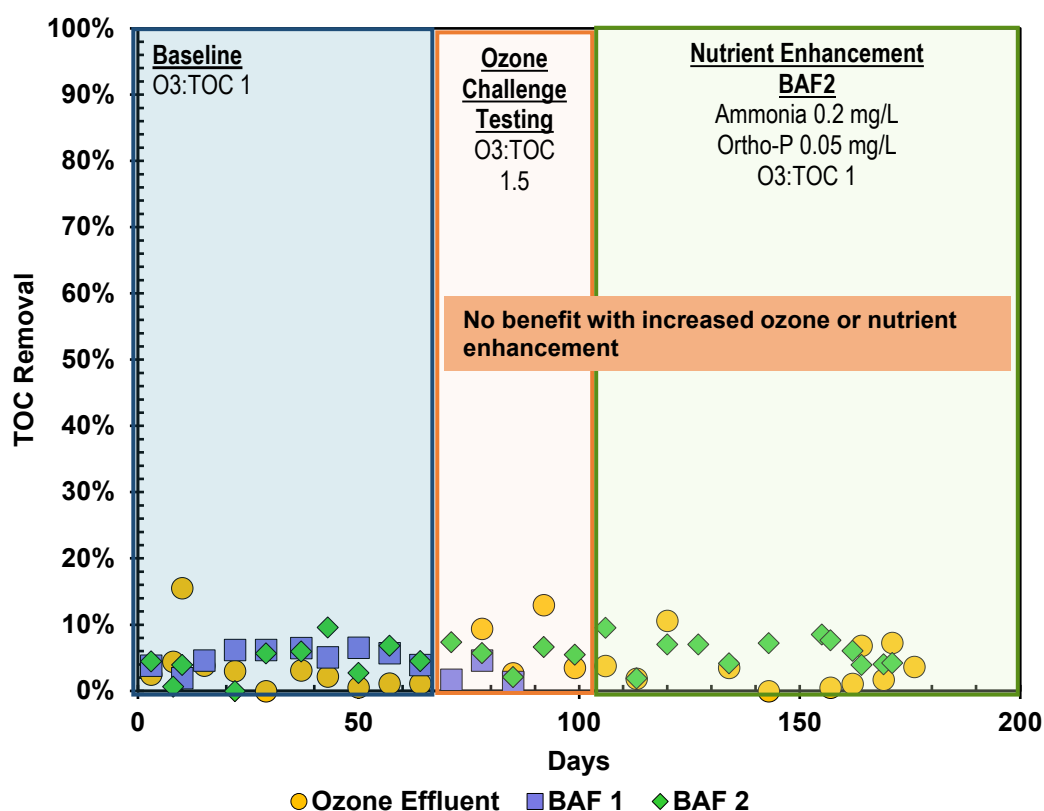
Phases	Days of Operation	Ozone Effluent	BAF 1 Effluent	BAF 2 Effluent	Filter Adsorber 1 Effluent	Filter Adsorber 2 Effluent
Baseline	66	1.7 ± 0.1	1.6 ± 0.1	1.6 ± 0.1	1.2 ± 0.3	-
Robustness	33	1.7 ± 0.1	1.6 ± 0.2	1.6 ± 0.1	1.5 ± 0.1	0.7 ± 0.3
Optimization	81	1.8 ± 0.1	-	1.4 ± 0.2	1.4 ± 0.1	1.4 ± 0.2
Entire Study	176	1.7 ± 0.1	1.6 ± 0.1	1.6 ± 0.1	1.4 ± 0.2	1.3 ± 0.3

Table 4-9: Average TOC Concentrations with Increasing Bed Volumes (GAC Contractor)

Days	Bed Volumes	GAC Contactor Effluent
40	2810	0.5 ± 0.1
80	5621	0.5 ± 0.1
120	8431	0.6 ± 0.2
182	12788	0.8 ± 0.3

Ozone Biofiltration

During baseline operation, both BAF columns (BAF 1 and BAF 2) were operated similarly and were fed from ozone effluent. Ozone was operated such that the ozone dose to influent TOC ratio was 1. As indicated in Figure 4-9, the TOC removal was poor for ozone and BAF (less than 10 percent) in which the average effluent TOC was 1.7 mg/L (ozone effluent) and 1.6 mg/L (BAF effluent). To improve TOC removal in BAF, the ozone dose was increased to maintain an ozone dose to influent TOC ratio of 1.5 during ozone challenge testing (i.e., robustness condition from day 67 to day 100, see Table 4-3). There was no significant improvement in TOC removal in BAF and the average effluent TOC was similar to baseline testing. The impact of nutrient addition on TOC removal in BAF was evaluated by the addition to BAF 2 of 0.2 mg/L-N of ammonium chloride and 0.05 mg/L-PO₄ of phosphoric acid. With nutrient augmentation, there was only marginal improvement in TOC removal in BAF 2 with an average TOC effluent of 1.4 mg/L.


Figure 4-9: TOC removal in Ozone and BAF during three different phases

GAC Contactor

Figure 4-10 and Figure 4-11 show the effluent TOC and TOC removal effectiveness in the GAC contactor at varying EBCT with increasing BV. TOC removal effectiveness reduced with increasing BV and the effluent TOC increased with increasing BV for all EBCTs. GAC BVs of 10,000 to 15,000 were needed to maintain consistent TOC values below the target range of 1.0 to 1.2 mg/L. The effluent TOC was similar for all EBCTs (at the same BV) and TOC removal was a function of BV, indicating adsorption as the dominant mechanism for TOC removal. Effluent TOC began plateauing around 25,000 to 30,000 BV, as seen by the TOC values in the GAC 4-minute EBCT contactor.

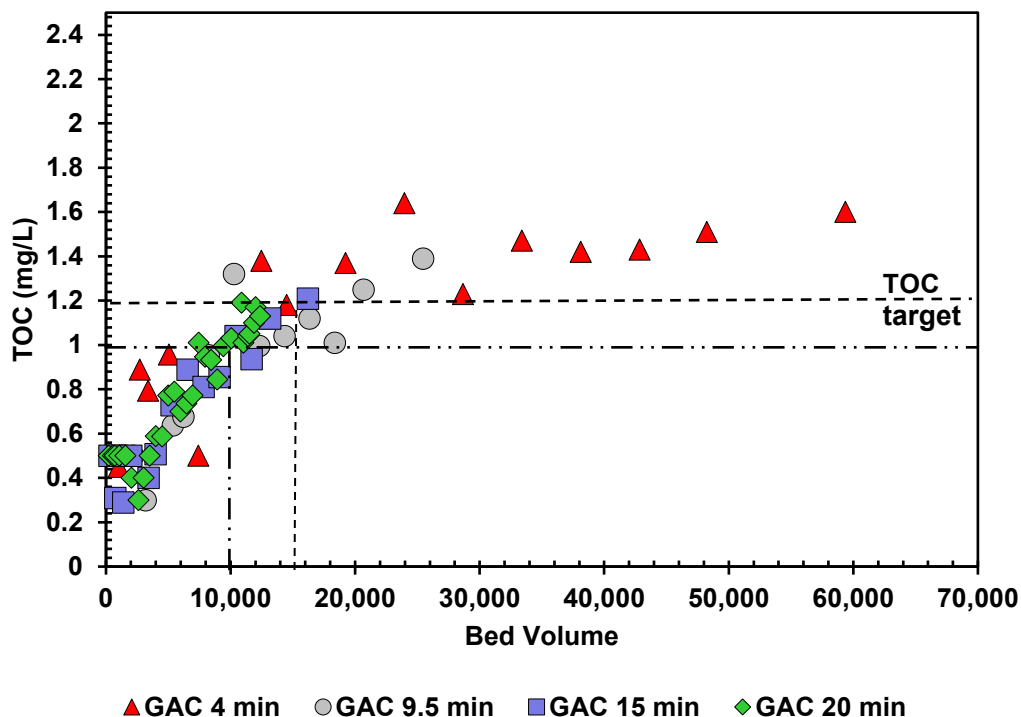


Figure 4-10: GAC contactor effluent TOC at different EBCT with increasing BV

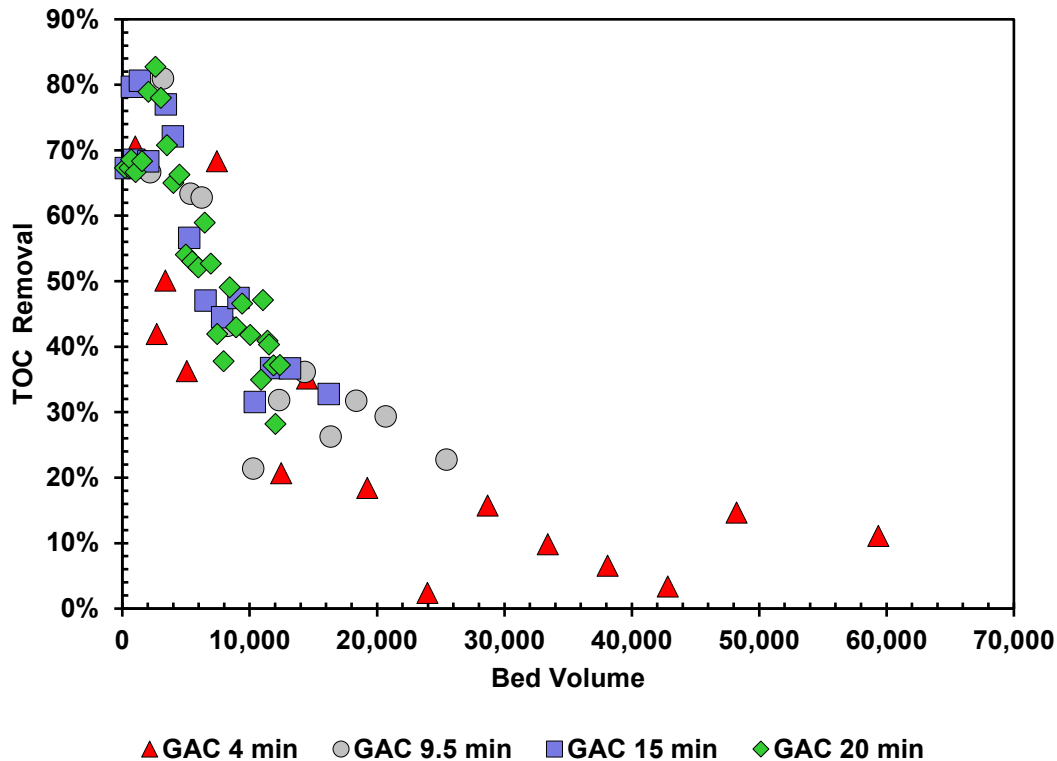


Figure 4-11: TOC removal in GAC contactor at different EBCT with increasing BV

Filter Adsorber

TOC removal in both filter adsorbers was comparable and followed the same trend as seen in Figure 4-12. Virgin media was used in both filter adsorbers. Thus, the TOC removal in both filter adsorbers decreased with increased pilot operation as the media became exhausted. After approximately 100 days of operation (approximately 28,000 BV), TOC removal in Filter Adsorber 1 reached steady state, indicating biodegradation due to biological growth on the media. The 33 percent TOC removal observed in Filter Adsorber 1 on Day 92 is considered an outlier and is not representative of TOC removal in Filter Adsorber 1. The effluent TOC in both filter adsorbers were below the target range of 1.0 to 1.2 mg/L in the initial phase but increased above 1.2 mg/L after 25 days (approximately 7,000 BV) of operation. The TOC removal in both filter adsorbers was still greater than both BAFs. Even after Filter Adsorber 1 turned biological (steady state), the TOC removal was approximately 15 percent while TOC removal in BAF was less than 10 percent.

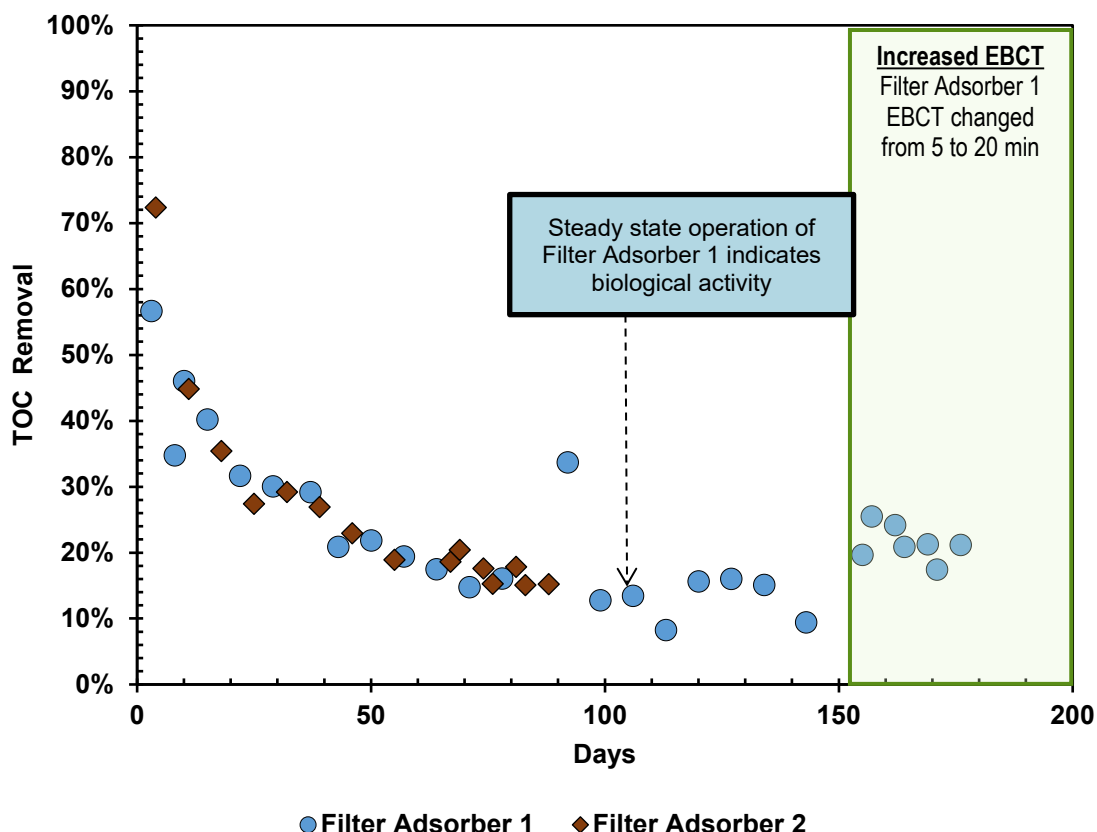


Figure 4-12: TOC removal in Filter Adsorbers 1 and 2

Filter Adsorber versus GAC contactor

The TOC removal in Filter Adsorber 1 improved (more than 20 percent) after increasing the EBCT to 20 minutes to match the GAC contactor EBCT. At this point, the filter adsorber media was already exhausted and had processed approximately 44,000 BV of water. The concept of increasing the EBCT in Filter Adsorber 1 was to determine if TOC removal similar to the GAC contactor can be achieved in filter adsorber by biodegradation, thus extending media life and saving operational cost associated with media replacement. The average effluent TOC for a filter adsorber after increasing EBCT was 1.4 ± 0.1 mg/L as compared to 1.1 ± 0.1 mg/L in the GAC contactor. Thus, the increase in EBCT resulted in improvement in TOC removal but was still not comparable to the GAC contactor and did not meet the TOC target range of 1.0 to 1.2 mg/L.

4.6.3 UV₂₅₄ Absorbance Results

Ozone Biofiltration

There was no significant reduction in total UV₂₅₄ absorbance by ozone as seen in Figure 4-13. Thus, there was no change in the aromaticity of the organic compounds present. These results differ from those obtained during bench-scale testing. As part of bench-scale testing, UV₂₅₄ samples were filtered but were not filtered for pilot-scale. Further, the settled water solids carryover and particulate metals (iron and manganese) from the existing WTP softening process may have resulted in increased ozone demand.

BAF 1 and BAF 2 reduced UV_{254} absorbance to an average of 0.030 and 0.031 cm^{-1} , indicating aromatic compounds were removed by biofiltration. Both BAFs could reduce UV_{254} absorbance but did not achieve the effluent UV_{254} absorbance target range of 0.015 to 0.02 cm^{-1} . Pilot operational phases did not impact UV_{254} absorbance reduction in ozone and BAFs. The variability in UV_{254} absorbance values for both ozone effluents and BAF effluents was reflective of the variability in the ozone influent UV_{254} absorbance values.

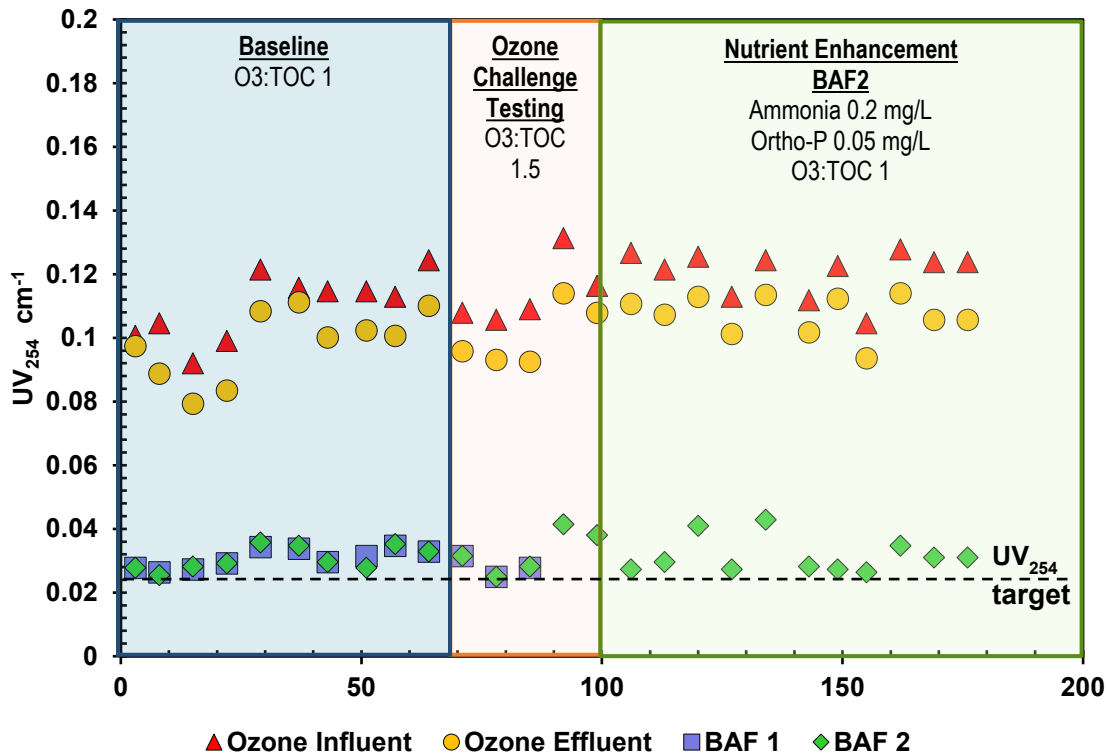


Figure 4-13: Ozone and BAF UV_{254} absorbance values during different pilot phases

GAC Contactor

As shown in Figure 4-14, total UV_{254} absorbance increased with increased BVs for GAC EBCTs of 9.5, 15, and 20 minutes. No trending was apparent for GAC EBCT of 4 minutes. UV_{254} absorbance values for all GAC EBCT locations were comparable for the same BV. BV above 20,000 resulted in UV_{254} absorbance values greater than 0.02 cm^{-1} . The GAC EBCT 15-minute contactor reached a UV_{254} absorbance of 0.03 cm^{-1} after 25,000 BV. DBP values at these BVs will necessitate GAC media replacement. This can be seasonal based on water demand and temperature changes in finished water within the distribution system.

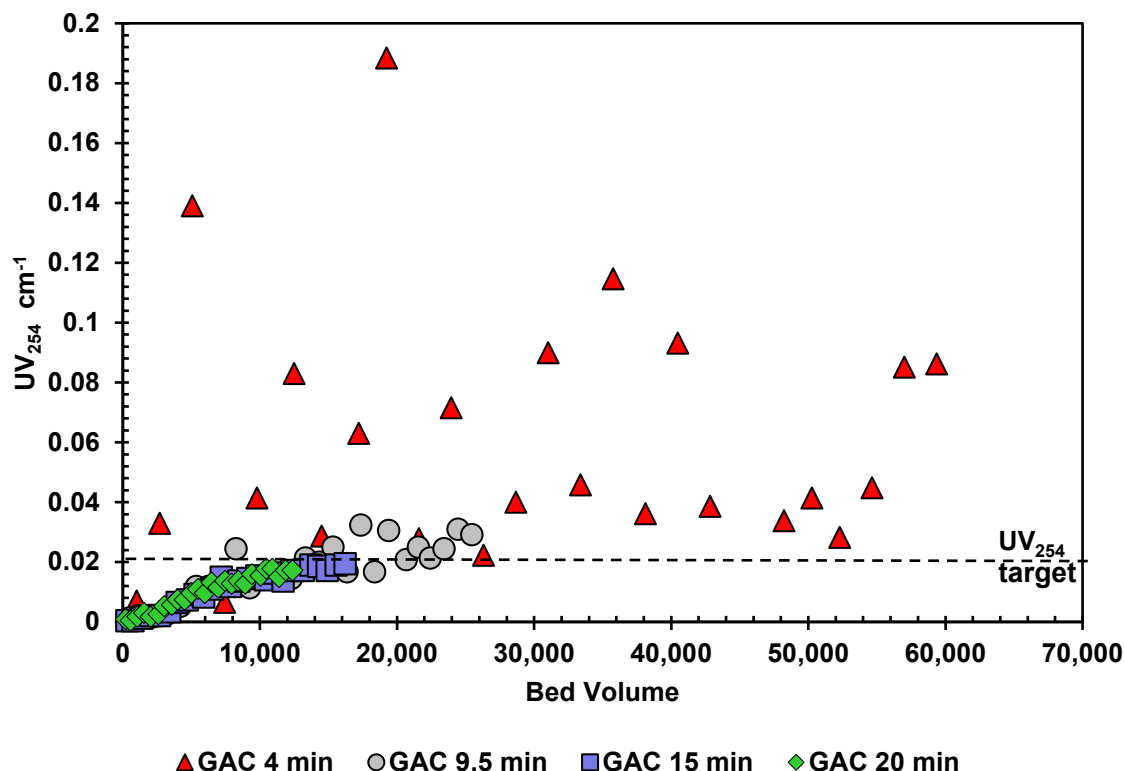


Figure 4-14: GAC contactor UV₂₅₄ absorbance values at different EBCT with increasing BV

Filter Adsorber

Figure 4-15 indicates the average total UV₂₅₄ absorbance values for Filter Adsorber 1 and 2 were 0.025 and 0.024 cm⁻¹, respectively. These values are not significantly higher than those for the BAF effluent. UV₂₅₄ absorbance was below the higher end target of 0.02 cm⁻¹ for both filter adsorbers during startup operation but increased above 0.02 cm⁻¹ after a month of operation as the GAC media was exhausted (approximately 8,500 BV). An increase in EBCT to 20 minutes in Filter Adsorber 1 reduced UV₂₅₄ absorbance to 0.022. This indicates improvement in the removal of aromatic compounds but was not comparable to the GAC contactor with 20 minutes EBCT.

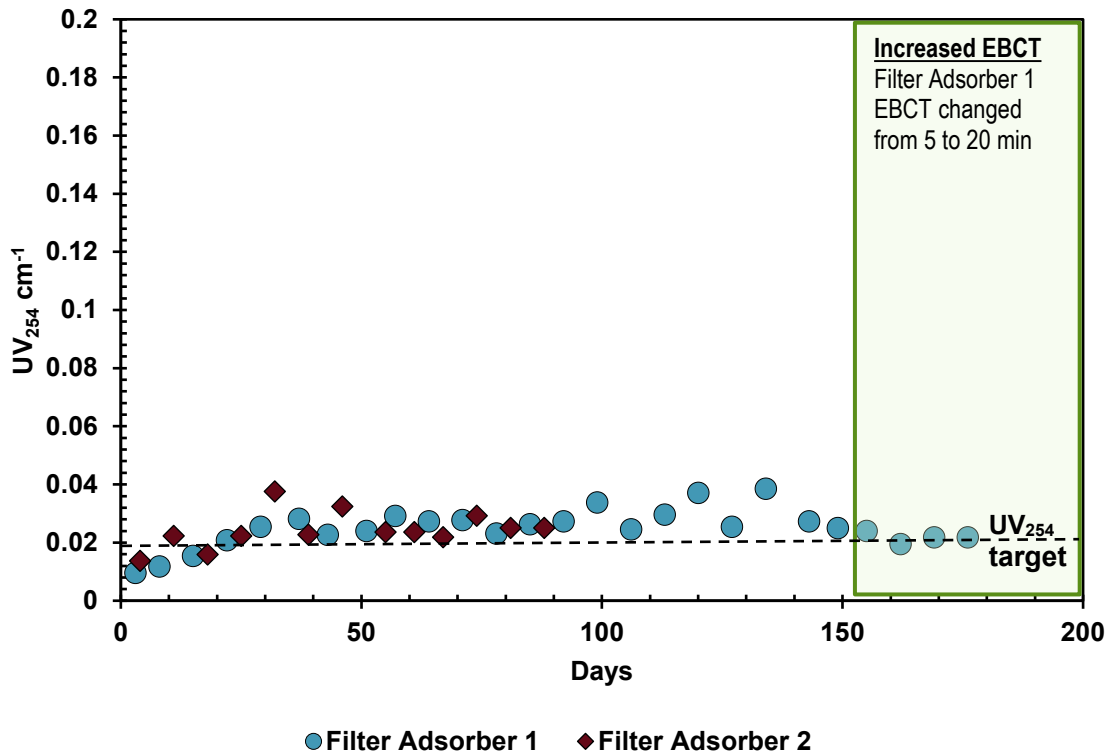


Figure 4-15: UV₂₅₄ absorbance values for Filter Adsorber 1 and 2 during pilot operation

4.6.4 Simulated Distribution System Results

Disinfection byproduct formation potential (DBP-FP) was determined for each treatment process by adding free chlorine (TTHM and HAA5) or chloramines (NDMA) and analyzing the samples after 3 days and 7 days. SDS testing for TTHM and HAA5 was conducted by adding sodium hypochlorite to achieve a 3 mg/L chlorine residual in all sample locations after 10 mins. Samples were allowed sit in water bath at 25°C for 3 or 7 days prior to TTHM and HAA5 analysis. The 3-day TTHM-FP and HAA5-FP showed that free chlorine accounts for 80 percent of TTHM and HAA5 formed after 7-days. NDMA-FP was determined by adding chlorine and ammonia (4:1 Cl₂ to NH₃-N ratio) to form 3 mg/L of monochloramine then allowing the samples to sit for 7 days before analyzing for NDMA.

HAA5-FP

HAA5 SDS values were below 80-percent of the MCL of 60 µg/L for all treatment processes, ozone influent, and GAC influent during the entire pilot duration (see Figure 4-16). Therefore, HAA5 formation was determined to not be an issue for this source water quality. HAA5 formation was the lowest in the GAC contactor, indicating that GAC adsorption is best for removing HAA5 precursors. HAA5 formation in ozone and BAF was comparable, with slight improvement in BAF after nutrient addition. Filter adsorbers performed better than BAF (prior to nutrient addition) at removing HAA5 precursors but were not as effective as the GAC contactor, even after increasing EBCT.

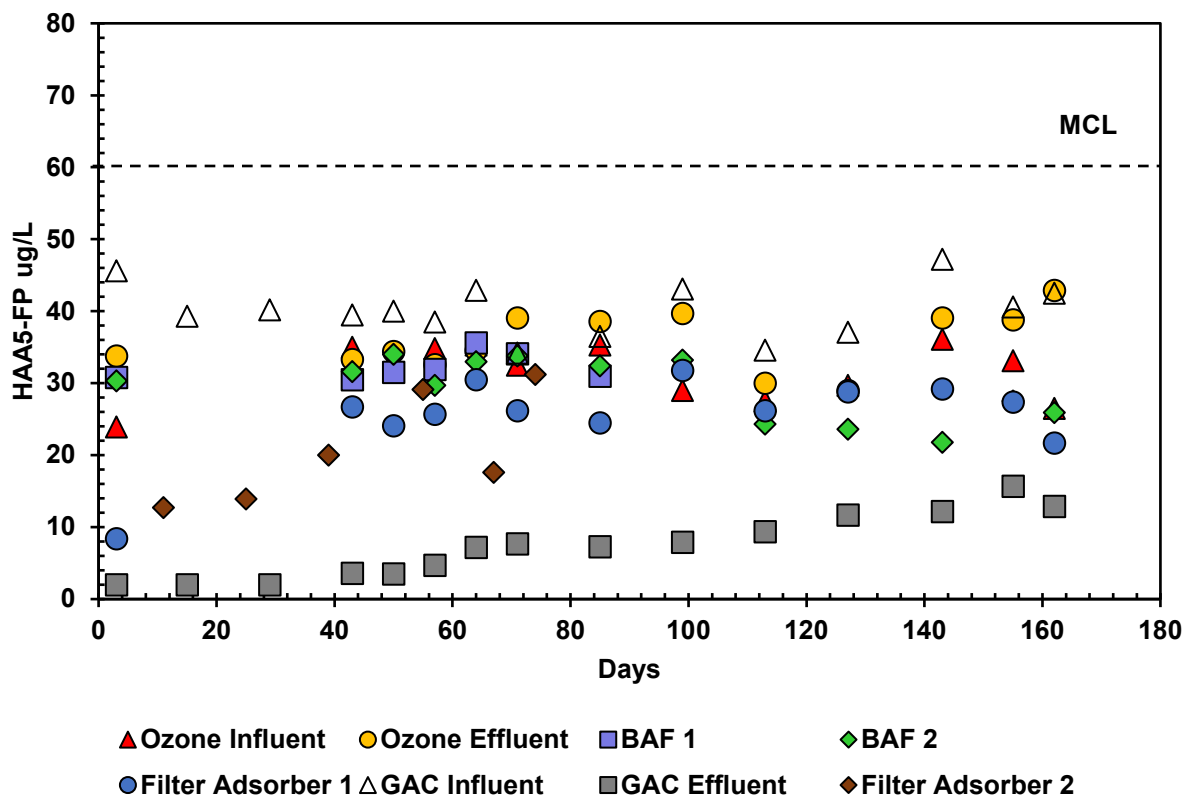


Figure 4-16: HAA5-FP in each treatment process after 7-day SDS test

TTHM-FP

Ozone Biofiltration

The SDS testing indicated TTHM-FP for ozone and BAFs was above the MCL, as shown in Figure 4-17. Baseline pilot operation showed that there was some increase in TTHM formation by ozone, with slight removal by BAF 1 and BAF 2. However, the overall TTHM formation in ozone and both BAFs was comparable to the ozone influent TTHM formation. Increasing ozone dose during ozone challenge testing did not impact TTHM formation and TTHM values were similar for ozone and BAF. There was marginal improvement in reduction of TTHM SDS values in BAF 2 after nutrients were added. The differential observed between ozone and BAF 2 TTHM-FP increased from 6.5 µg/L during baseline testing to 9.6 µg/L during the nutrient enhancement phase, indicating slight improvement in the removal of TTHM precursors after nutrients were added to BAF 2.

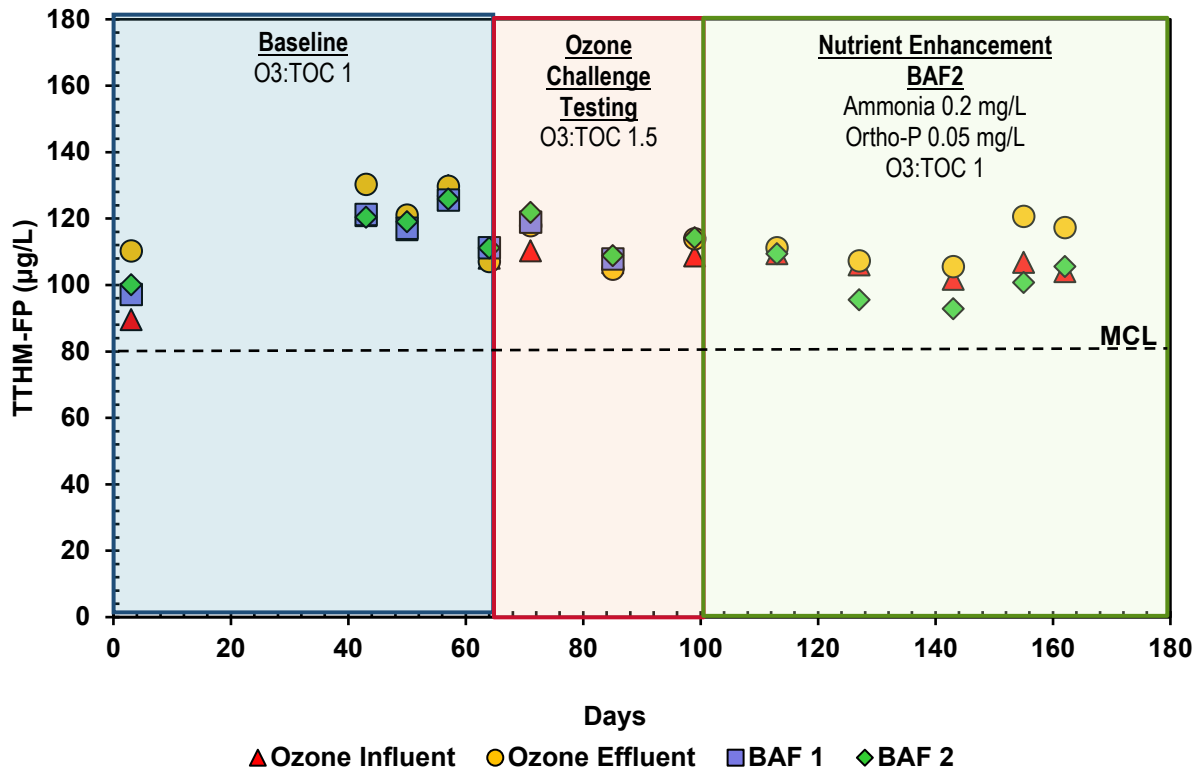


Figure 4-17: TTHM-FP in Ozone and BAF after 7-day SDS test during different phases of pilot operation

GAC Contactor

Figure 4-18 shows that even though TTHM formation in GAC influent was above the 80 µg/L MCL, TTHM formation in 20 minute EBCT GAC contactor effluent was consistently below the MCL (up to 11,000 BV). This shows that GAC adsorption is highly effective for removal of TTHM precursors and reduces TTHM formation potential. To better understand the GAC media exhaustion for TTHM removal and determine BV needed for media replacement, TTHM formation was calculated for different EBCT and BV as shown in Figure 4-19. Correlation between DBP and UV₂₅₄ absorbance was developed for the GAC contactor. This correlation along with UV₂₅₄ absorbance values at different EBCT were used for calculating TTHM values at different EBCT. Figure 4-19 shows that an increase in TTHM with BV was similar for all EBCTs. BV above 15,000 resulted in an increase in TTHM above the MCL. The GAC 4-minute EBCT was excluded due to the variability in the UV₂₅₄ absorbance values.

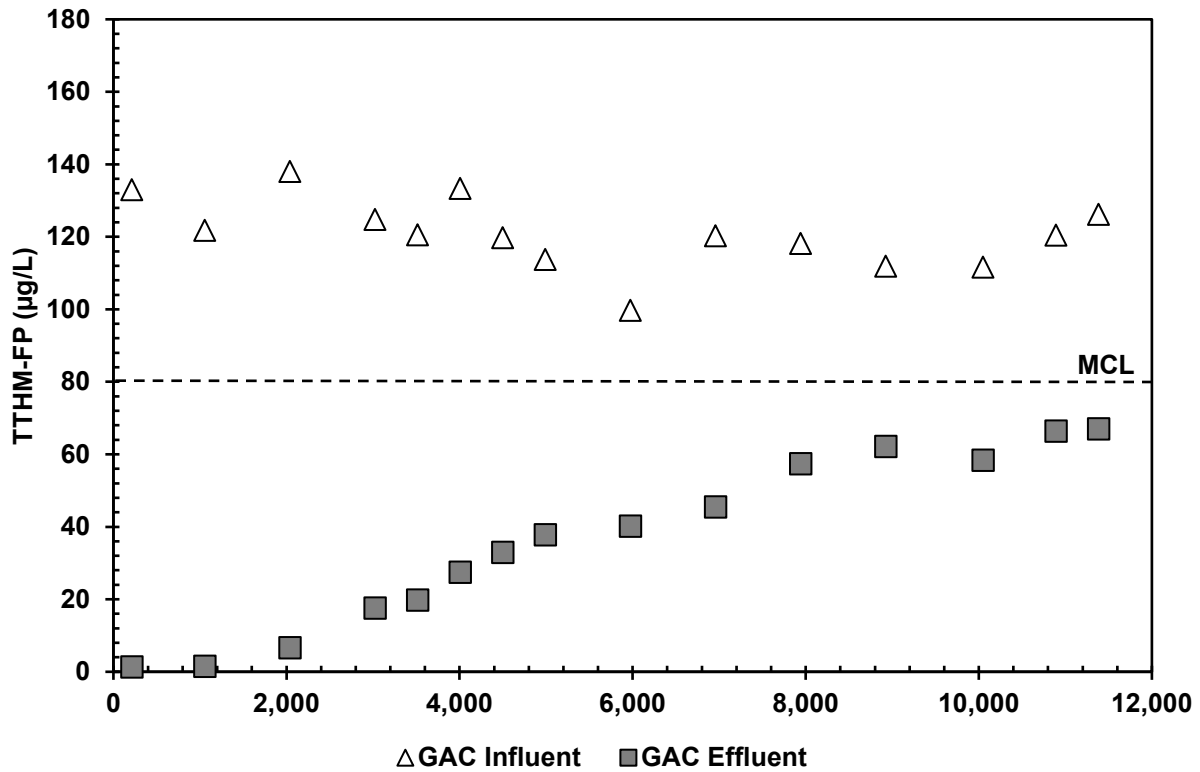


Figure 4-18: TTHM-FP in GAC contactor after 7-day SDS test with increasing BV

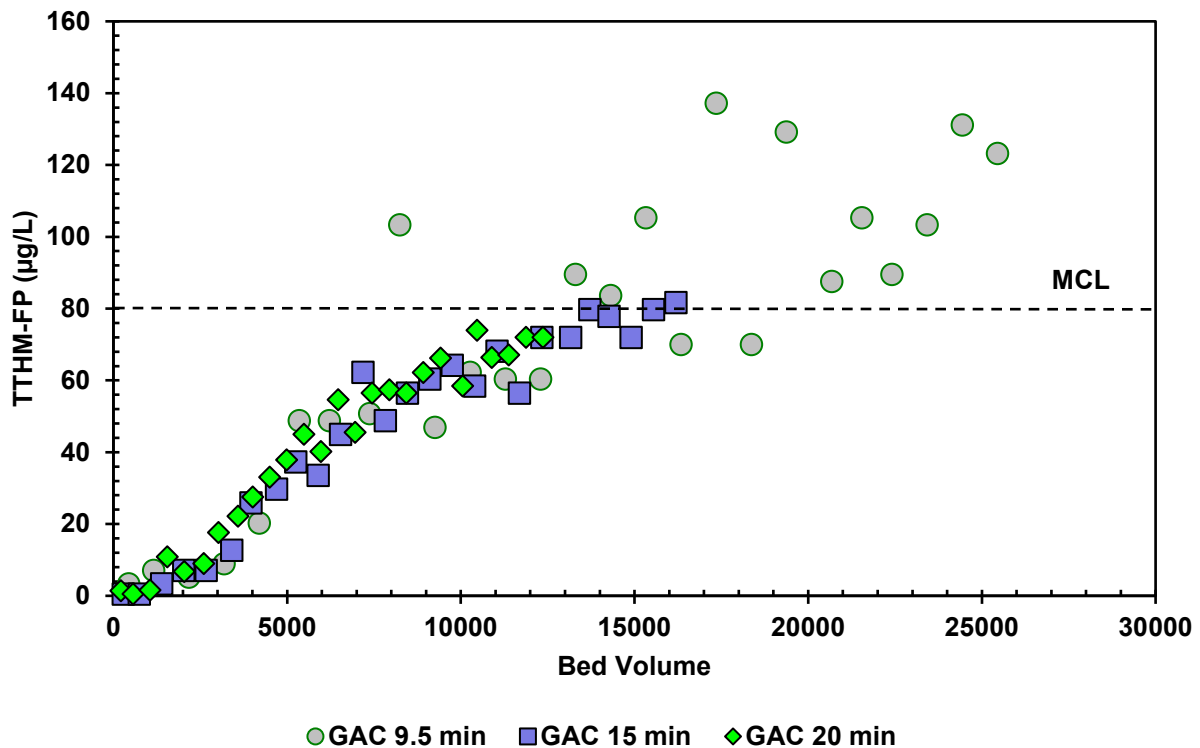


Figure 4-19: TTHM-FP in GAC contactor at different EBCT (Calculated based on TTHM SDS vs UV₂₅₄ correlation)

Filter Adsorber

As presented in Figure 4-20, TTHM formation in Filter Adsorber 1 and 2 increased with media exhaustion and was above the MCL after a month of pilot operation (approximately 8,500 BV). Steady state operation in Filter Adsorber 1 was observed after 2 to 3 months of pilot operation (approximately 28,000 BV) with consistent TTHM SDS values (average 102 µg/L). These values were lower than BAF 2 (average 109 µg/L), indicating slightly better performance in TTHM precursor removal by filter adsorber compared to BAF during steady state. An increase in EBCT in Filter Adsorber 2 did not significantly reduce TTHM formation and TTHM SDS values continued to stay above the MCL.

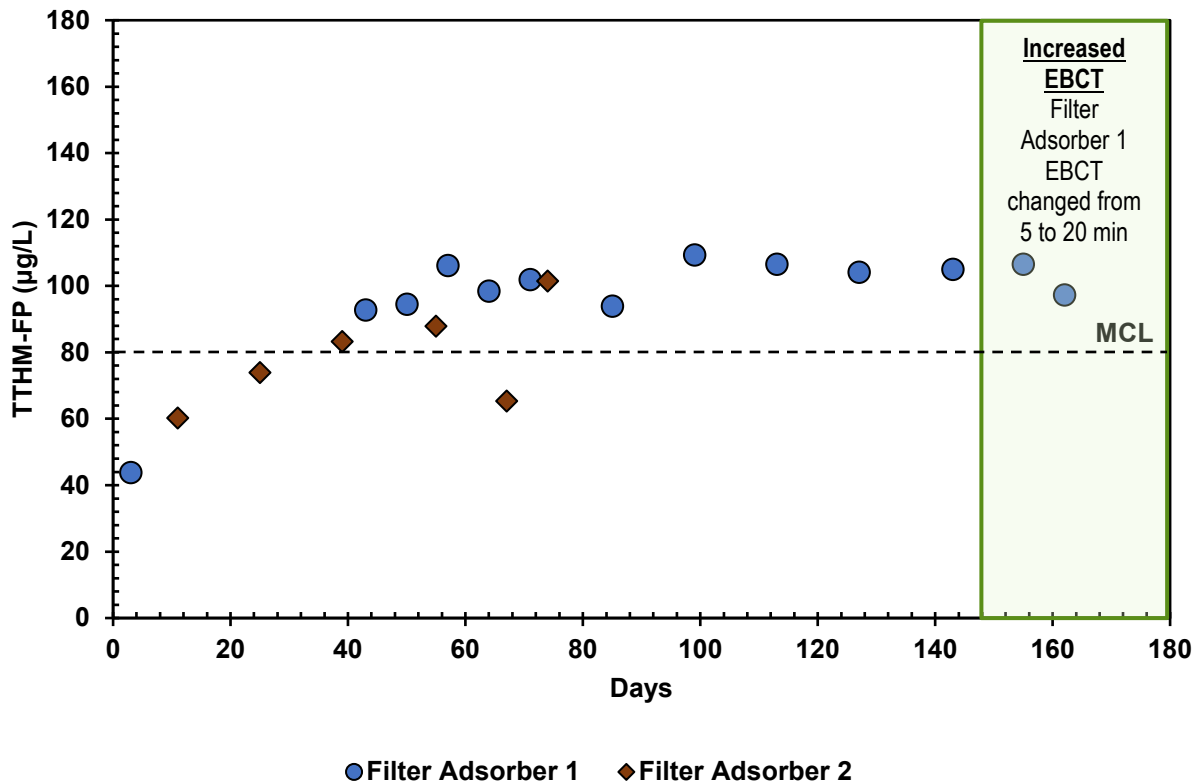


Figure 4-20: TTHM-FP in Filter Adsorber 1 and 2 after 7-day SDS test during pilot duration

DBP Speciation

Based on the EPA Stage 2 Disinfection Byproduct Rule, the MCL for TTHM and HAA5 apply to the sum of individual compounds. However, as shown in Table 4-10, there are maximum contaminant level goals (MCLGs) defined for individual TTHMs and HAA5.

Table 4-10: EPA Stage 2 DBP Rule MCL and MCLG for TTHM and HAA5

Stage 2 DBP Rule (EPA 2010)		
Regulated Contaminants	MCL (µg/L)	MCLG (µg/L)
TTHM	80	-
Chloroform	-	70
Bromodichloromethane	-	Zero
Dibromochloromethane	-	60
Bromoform	-	Zero
HAA5	60	-
Monochloroacetic acid	-	70
Dichloroacetic acid	-	Zero
Trichloroacetic acid	-	20
Bromoacetic acid	-	-
Dibromoacetic acid	-	-

Figure 4-21 and Figure 4-22 show the average formation of individual TTHMs and HAA5 for each pilot treatment process, respectively.

For individual TTHMs, chloroform was the dominant trihalomethane but was removed below the MCLG by filter adsorbers and the GAC contactor. Bromodichloromethane was the second highest trihalomethane and was detected in all sample locations, with the lowest concentration detected in the GAC contactor. Dibromochloromethane was below MCLG in the source water as well as all pilot treatment processes, with the GAC contactor outperforming all other processes. Bromoform was also detected in all sample locations at lower concentrations. It is important to consider that brominated DBPs have a greater mass and are considered to have greater toxicity. GAC was more effective at removing precursors that formed dibromochloromethane and bromodichloromethane.

As mentioned previously, the sum of HAA5 compounds was below the MCL. Monochloro-acetic acid and trichloro-acetic acid were below the MCLG in all sample locations and was removed by filter adsorbers and the GAC contactor. Dichloroacetic acid was detected in all sample locations and was present in the highest concentrations compared to other HAA5. The GAC contactor outperformed the other processes in overall removal of dichloroacetic acid. There was negligible removal of dibromoacetic acid in all treatment processes. Monobromoacetic acid was not detected in any sample locations.

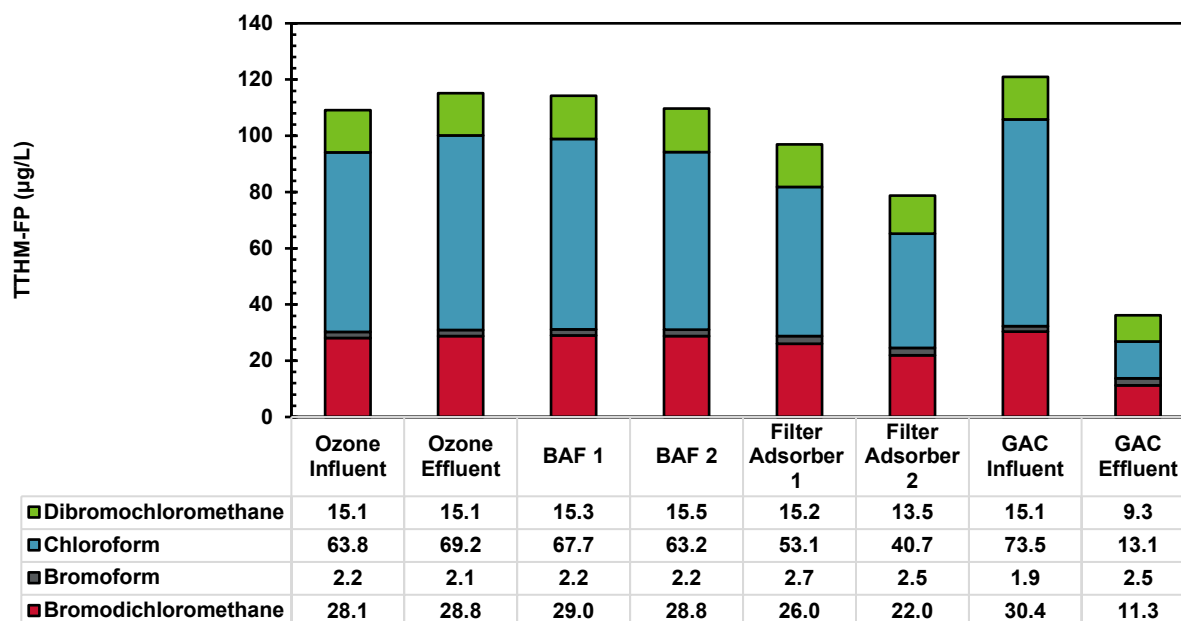


Figure 4-21: Average formation of Trihalomethanes in each pilot treatment process after 7-day SDS test

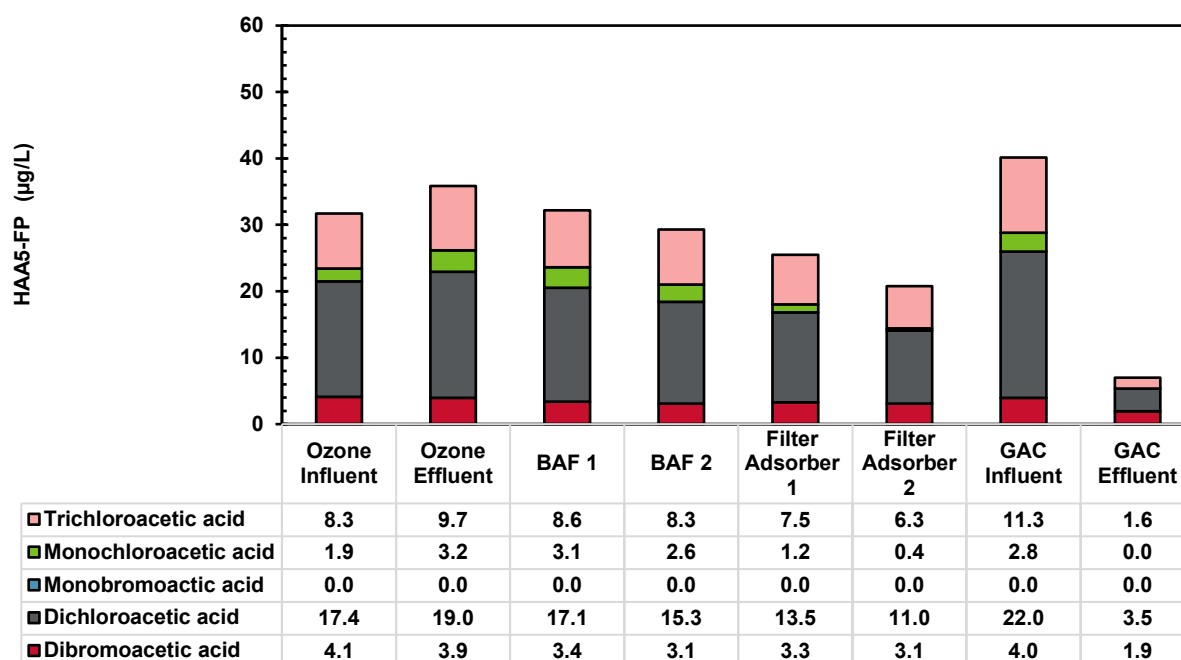


Figure 4-22: Average formation of Haloacetic acids in each pilot treatment process after 7-day SDS test

N-Nitrosodimethylamine

N-Nitrosodimethylamine (NDMA) is a disinfection byproduct that can be formed by chloramines in drinking water. NDMA is currently not regulated by USEPA; however, some states have drinking water guidelines for NDMA. Samples for NDMA were collected at the ozone effluents, Filter Adsorber 1, and

the GAC contactor. Additionally, samples were collected from WTP finished water and customer tap water. For each sample, chlorine and ammonia (4:1 Cl₂ to NH₃-N ratio) were added to form 3 mg/L of monochloramine. The samples sat for 7 days before analyzing for NDMA.

Table 4-11 shows the NDMA results before (Day 0) and after (Day 7). The NDMA results for Day 0 for all sample locations were below the method reporting limit of 2 ng/L. NDMA was formed at concentrations lower than 10 ng/L after 7 days for all sample locations. There are no clear distinctions in NDMA formation for each of the processes, thus NDMA precursor removal could not be predicted. With NDMA levels below the method reporting limits in the WTP finished water and Columbia tap water, NDMA does not appear to be an issue based on the sampling conducted during this study. However, it is recommended that the City consider long-term monitoring of NDMA in the distribution system to better characterize its formation with chloramine secondary disinfection.

Table 4-11: NDMA and NDMA-FP in the pilot treatment processes

Sample Location	NDMA (ng/L) ¹					
	Sampling Event 1		Sampling Event 2		Sampling Event 3	
	Day 0	Day 7	Day 0	Day 7	Day 0	Day 7
Ozone Effluent	N/A	N/A	2	4.3	2	6.6
Filter Adsorber 1 (20 min EBCT)	N/A	N/A	2	3.8	2	6.5
GAC Contactor Influent	N/A	N/A	2	4.8	2	4.8
GAC Contactor Effluent	N/A	N/A	2	6.1	2	6.5
WTP Finished Water	2	5	N/A	N/A	N/A	N/A
Columbia Tap Water	2	N/A	N/A	N/A	N/A	N/A

¹ The analytical lab method reporting limit for NDMA was 2 ng/L

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5 Alternatives Analysis

The objective of this study was to determine the best treatment technology for removing organic compounds and reducing the formation of disinfection byproducts while improving overall water quality. The desktop analysis concluded that enhanced lime softening was not viable to achieve future finished water quality considerations. Bench-scale testing was conducted to inform pilot operation and test air stripping of post-filtration water for DBP reduction. However, bench-scale results indicated air stripping is not effective due to the slow formation of TTHMs and the continuation of TTHM-FP following aeration.

Pilot-scale testing evaluated three different treatment options—post softening ozonation followed by BAF, post-filtration GAC contactors, and post-softening ozonation followed by GAC filter adsorbers. Formation of TTHM and HAA5 over a period of 7-days after the addition of 3 mg/L chlorine was used to evaluate the performance of the three pilot treatment processes. HAA5 formation was below the MCL in the pilot source water and following all pilot treatment processes.

As stated above, based on the correlation between DBPs precursors (TOC, and UV_{254} absorbance) a TOC target range of 1.0 to 1.2 mg/L and a UV_{254} absorbance target range of 0.015 to 0.02 cm^{-1} was needed to maintain a TTHM formation potential below the MCL. A summary of the pilot-scale testing results is as follows:

1. Ozone-BAF: Pre-exhausted GAC media was used in the two (2) BAF filter columns. The TOC removal in ozone-BAF was 5-percent and did not significantly improve after increasing ozone dose or nutrient enhancement. Average effluent TOC values were 1.6 mg/L throughout all operational phases. UV_{254} absorbance was reduced by BAF to 0.03 cm^{-1} but did not meet the project target range of 0.015 to 0.02 cm^{-1} . There was no significant TTHM or HAA5 formation by ozone and BAF; however, there was minimal formation potential reduction, indicating poor removal of DBP precursors. Average TTHM-FP was 115 $\mu g/L$ after ozone and 114 $\mu g/L$ after BAF. Nutrient addition in BAF led to improved TTHM-FP reduction (103 $\mu g/L$) but exceeded the 80 $\mu g/L$ MCL. The ozone-BAF treatment performance was inconsistent with previous case studies and full-scale biofilter applications. Potential confounding variables include high levels of settled water solids carryover from the existing softening system. Calcium scaling was observed on the previously exhausted GAC media. Life cycle costs for ozone-BAF can be significantly lower as compared to GAC. This technology may be revisited after the current lime softening improvements are complete, when potentially greater TOC reduction is achieved as well as possible scaling and solids carryover experienced during piloting are reduced are eliminated.

2. GAC Contactor: The GAC contactor was successful in achieving TOC, UV_{254} absorbance, and DBP project targets. DBP-FP and TOC correlations developed during pilot-scale testing were similar to those obtained for bench-scale testing. TOC removal in the GAC contactor was a function of the number of treated BVs. GAC-treated water TOC values remained below the project target of 1.0 to 1.2 mg/L at conditions up to 10,000 to 15,000 BV. This was confirmed at 4-, 9.5-, 15-, and 20-minute EBCT. Similarly, BV above 20,000 resulted in UV_{254} values above 0.02 cm^{-1} and BV above 15,000 resulted in TTHM-FP above MCL.

3. Filter Adsorbers: The GAC filter adsorbers showed similar initial performance to the GAC contactors. TOC and DBP-FP removal decreased with time as media was exhausted, although more rapidly than the GAC contactors (due to a shallower depth and lower EBCT). TOC removal reached steady state (average effluent TOC 1.5 mg/L with 13 percent TOC removal) after approximately 100 days of operation (approximately 28,000 BV). UV_{254} absorbance increased above 0.02 cm^{-1} after a

month of operation and increased to 0.025 cm^{-1} after steady state operation. TTHM-FP also exceeded MCL after a month of operation (approximately 8,500 BV), with average values of $102 \text{ }\mu\text{g/L}$. Overall, filter adsorber performance was better than BAF but was not comparable to GAC. Increasing EBCT to 20 minutes in Filter Adsorber 1 improved TOC and TTHM-FP removal but did not meet the project TOC, UV_{254} , or TTHM targets.

The GAC contactor outperformed all other pilot treatment technologies for TOC, UV_{254} absorbance, and DBP removal. Based on the TOC and DBP values, GAC media may need replacement at 10,000 to 15,000 BV (once every 4.5 to 7 months at 20-minute EBCT) to achieve the 80-percent of the MCL and the MCL, respectively. However, greater TOC reduction may be achievable with enhanced softening and coagulant addition. Therefore, GAC replacement frequency may be revisited after the upcoming improvements are implemented at full-scale. Based on the effluent water quality achieved, the GAC contactor is the recommended treatment process for minimizing DBP formation and complying with study targets to potential revert to free chlorine secondary disinfection. GAC has the added benefit of removing many CECs that may be present in the raw water now or in the future.

6 Recommended Alternative

As detailed in the previous sections, GAC contactors were determined to be the most viable technology and are, therefore, the recommended treatment alternative if the City elects to revert to free chlorine secondary disinfection. GAC contactors reduce TOC and DBP formation potential to the extent necessary to allow the City to revert to free chlorine secondary disinfection. This section expands on the GAC contactor alternative to provide conceptual level facility sizing, design criteria, site plan layout, hydraulic analysis, and capital and life cycle cost estimates.

Adsorption is the process in which individual contaminant molecules, such as organic compounds, attach to the surface of an impermeable solid, such as activated carbon. GAC contact is a commonly implemented adsorption method. GAC contactors can be either pressure or gravity systems. In general, gravity systems are preferred for facilities over 10 MGD because a comparable economy of scale is not possible with prefabricated pressure tank systems. GAC gravity contactor components are very similar to conventional gravity filters, such as those in operation at the McBaine WTP. The primary difference is the media selection. A GAC contactor will consist of the GAC media (as piloted), support media, and an underdrain system to collect filtered water and distribute backwash water throughout the filter. Contactor system equipment also includes troughs, control valves, instrumentation, and backwash pumps.

The conceptual design development depends on several conditions including site constraints, cost, procurement requirements, desired operational flexibility, optimization strategies, and overall process train objectives. The recommended GAC contactor improvements for the Columbia McBaine WTP includes the following:

- Convert existing high service pumps to transfer pumps
- New post-filter GAC contactor building
- New clearwell
- New high service pumps

Given the depth of the existing McBaine WTP filters, the existing high service pumps will need to be converted to transfer pumps to amend the hydraulic profile and convey flows to the new GAC system. A new high service pump station will be constructed downstream of the new GAC system to convey finished water to the distribution system. The hydraulic profile depicted in Figure 6-1 illustrates the integration a new GAC system into the existing facility.



Water fed to the GAC contactors should have minimal to no chlorine present as the adsorption sites will consume the chlorine, depleting the effectiveness and reducing the GAC media life. The following free chlorine disinfection (FCD) options are viable for use with GAC contactors at the McBaine WTP.

- FCD Option 1: Continue to provide primary chlorination with free chlorine in the secondary basins. This alternative will provide disinfection contact time upstream of GAC and will result in formation of some DBPs prior to the GAC contactor. A secondary free chlorine dose will be required after GAC media in the high service pump finished water wetwell to achieve the necessary distribution system residual. The benefits of this option are maximizing the use of the existing secondary basins and baffles for primary disinfection and eliminates the need for additional finished water clearwells for disinfection (4 MG total required). There is some precedence in the industry to implement primary disinfection prior to GAC, thereby, converting precursors to DBPs which are more efficiently adsorbed with GAC than the precursors.
- FCD Option 2: Provide primary chlorination with free chlorine downstream of the GAC media and achieve CT with new clearwells (4 MGD total required). However, if located below grade the clearwells will be costly due to the required size and the high groundwater. If located above grade the clearwells will be costly due to the likely need for an additional 32 MGD transfer pump station.

FCD Option 1 will be carried forward in this analysis. A new 1 MG high service pump finished water wetwell will be integrated within the GAC facility below the GAC filters to accommodate the new high service pumps within the new footprint. The existing secondary basins provide the required contact time (CT) to achieve 99.9 percent or 3-log inactivation or removal of giardia lamblia cysts, thus meeting the ground water under the direct influence (GWUDI) water quality standards.

Table 6-1 presents a summary of GAC contactor facility design criteria. The N+1 condition indicates that full plant capacity can be treated with only seven (7) of eight (8) contactors. However, it is recommended that all eight (8) contactors be in service during normal plant operations to avoid degradation of the media resulting from excessive biomass growth and slime formation.

Table 6-1 Design Criteria (GAC Contactor)

Design Parameter	Value	Unit
Design capacity	32	MGD
EBCT	20	minutes
Number of GAC Contactors	Eight (N+1 mode of operation)	-
Contactor surface area	635	square feet (sf)
Surface loading rate	5.0	gpm/sf
Contactor width	21	feet
Contactor length	31	feet
GAC Media depth	13.37	feet
Contactor Free Board	2.0	feet
Clean Bed HL (assumed)	3.0	feet
Dirty Bed HL (allocated)	6.0	feet
Filter Gallery Width	23.0	feet
Building Length	59	feet
Building Width	178	feet
Building Height	40	feet
Finished Water Wetwell Volume	1,000,000	gal
Finished Water Wetwell Depth	15	feet

As detailed in Table 6-1 the approximate GAC facility footprint is approximately 59-ft by 178-ft, including GAC filters, finished water wetwell, and high service pumps. See Figure 6-2 below for a plan view of the conceptual GAC building layout.


Figure 6-2 Conceptual Building Layout (GAC Contactor)

The existing McBaine WTP is located within a secondary levee for flood protection. However, there is minimal space available for future improvements within this footprint. For the purposes of this evaluation, the GAC facility is to be located in the northwest corner of the site, within the levee, to maximize the available space and provide for future operation and maintenance accessibility. Figure 6-3 below illustrates an isometric view of the building on site, located north of the existing aerators. The isometric view has the roof and south wall of the GAC facility removed for clarity.

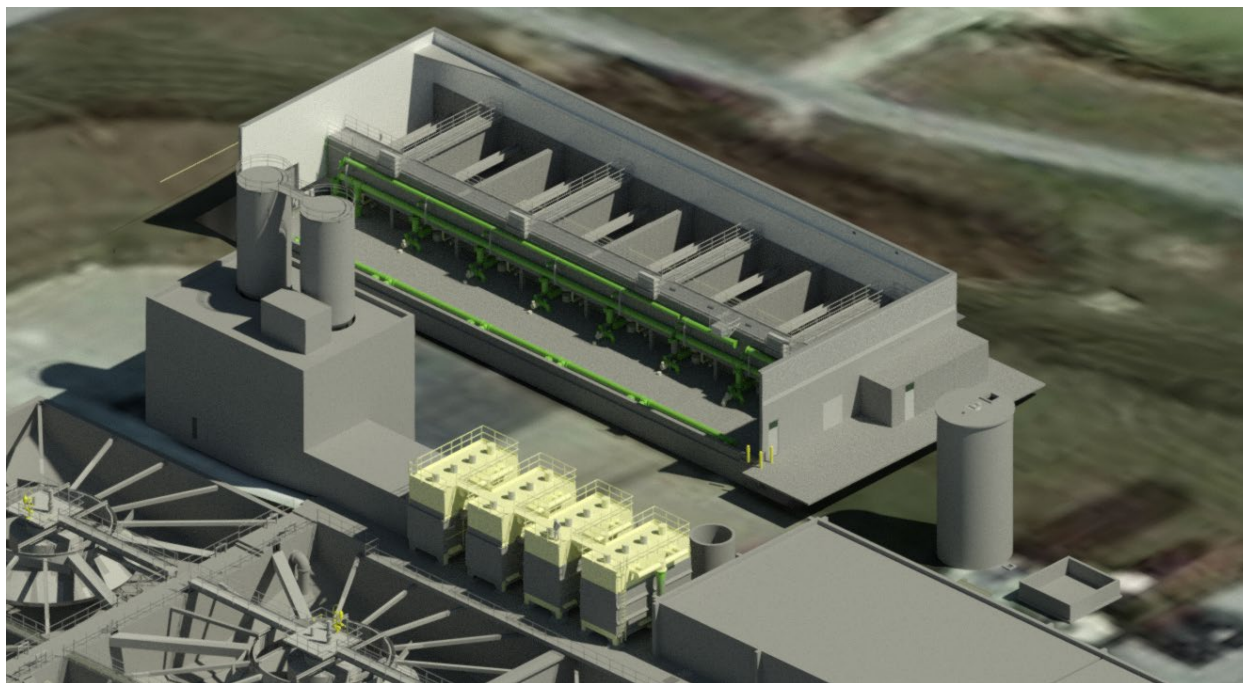


Figure 6-3 Conceptual Site Plan (GAC Contactor)

This section summarizes the opinion of probable construction cost for the new post-filter GAC facility with finished water wet well and high service pumps. A Class 5 Cost Estimate was completed as part of this evaluation and is presented in Table 6 2. A Class 5 Estimate, as defined by AACE, is typical for conceptual design or screening projects. The estimate is presented in 2021 dollars including a 25-percent general contingency. The general contingency factor is intended to include design, bidding, and construction phase contingencies for estimating at a planning or programming level of detail. It is noted that the current construction bidding market is volatile given recent material cost increases and other pandemic impacts. With the uncertainty regarding when this potential future project may be implemented, additional contingencies to adjust for further market volatility have not been included at this time.

Table 6-2 Class 5 Cost Estimate (GAC Contactor)

Total Class 5 Construction Cost Estimate	\$46,700,000
<i>Class 5 Range Low (-15%)</i>	<i>\$39,700,000</i>
<i>Class 5 Range High (+25%)</i>	<i>\$58,400,000</i>

Table 6-3 below presents the simplified lifecycle costs for the new GAC facility. The lifecycle cost analysis assumes a 20-year net present value (NPV) at a 4-percent discount rate and a 5-percent escalation rate. The operation and maintenance cost includes the GAC media replacement based on average day demand, a TOC target range of 1.0 to 1.2 mg/L and estimated operating cost of power for the new facility.

Table 6-3 Life Cycle Cost (GAC Contactor)

Item	Cost (\$)
Annual GAC Replacement Cost	\$2,670,000 - \$4,160,000
Annual Power Cost	\$20,000
Total Annual Operating Cost	\$2,690,000 - \$4,180,000
20 year Present Worth	\$98,700,000 - \$127,300,000

With consideration to the high annual operating costs outlined above, utilizing additional coagulants or enhanced lime softening in combination with carbon dioxide feed and future GAC contactors may extend GAC media life (not included in the cost estimate). Additional enhanced lime softening testing may be considered to establish actual TOC reduction rates achievable with these combined treatment processes. Maximizing TOC reduction with the lime softening facilities can reduce influent TOC to the GAC contactors, extending the GAC media replacement frequency, thereby, reducing annual operating costs. While this may increase the lime feed rate, associated chemical costs, and solids production and management, the net result will likely yield a life cycle cost savings.

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